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A Limited Rotary-Wing Flight Investigation of Hyperstereo in Helmet-Mounted Display Designs

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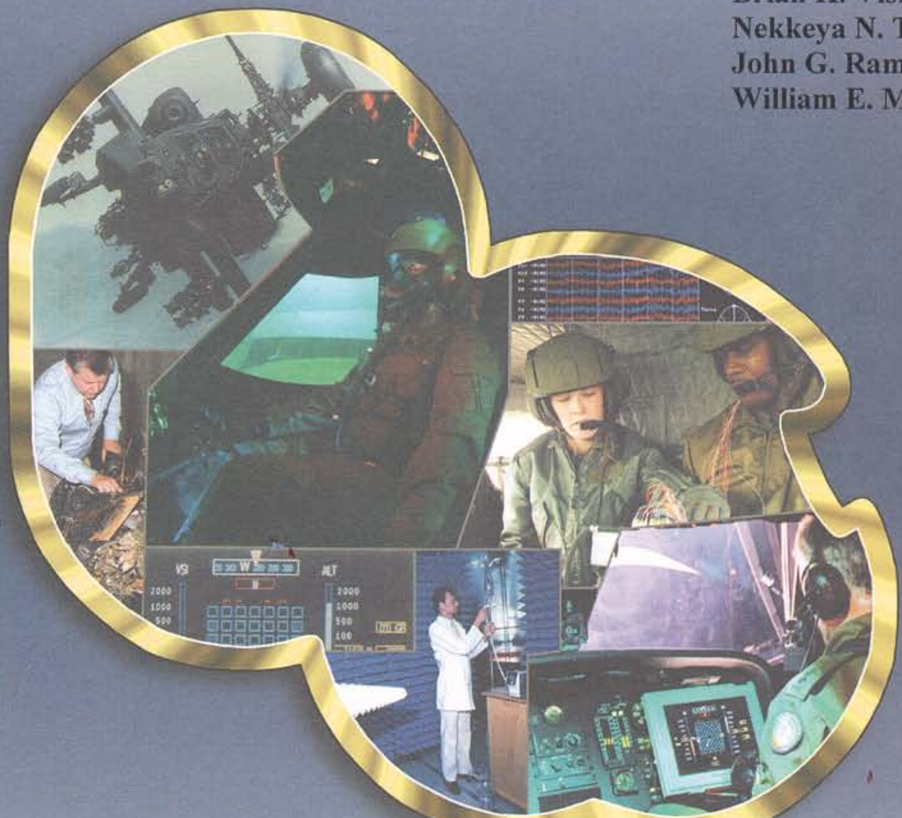

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14. ABSTRACT
A number of currently proposed helmet-mounted display (HMD) designs relocate image intensification (I2) tubes to the sides of the helmet. Such a design approach induces a visual condition referred to as hyperstereo vision (or hyperstereopsis). This condition manifests itself to the user as an exaggerated sense of depth perception, causing near- to mid-range objects to appear closer than they actually are. Hyperstereopsis is potentially a major concern for helicopter operations that are conducted at low altitudes. As part of a limited flight study to investigate this phenomenon, five rated U.S. Army aviators, as technical observers (hands-off-the-controls), wore a hyperstereo HMD during the conduct of a series if 13 standard maneuvers. Two subject aviators acquired a total of eight hours and three aviators a single hour of flight. Using a post-flight questionnaire, these aviators were asked to compare their visual experiences to that of normal I2-aided flight. Depth perception at distances below 300 feet was identified as the greatest challenge. The two 8-hour aviators reported a 5-8 hour “adaptation” period for most maneuvers.

15. SUBJECT TERMS
Helmet-mounted display, HMD, image intensification, hyperstereo, hyperstereopsis

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Introduction

Helmet-mounted displays (HMDs) have been a mainstay in military aviation since the 1970s. Within the U.S. Army, night vision devices, most commonly known as night vision goggles (NVGs), were introduced for use in helicopters in 1973. These devices, based on the principle of image intensification (I^2), have provided aviators with the capability to operate at night (McLean et al., 1998). The U.S. Army aviation version of these devices, which was fielded in the early 1980s, is the Aviator's Night Vision Imaging System (ANVIS), which uses enhanced 3rd generation (GEN III+) image intensifier tubes (figure 1).

After NVGs, the U.S. Army's most established HMD is the Integrated Helmet and Display Sighting System (IHADSS) fielded on the AH-64 Apache helicopter (figure 1). This HMD is a monocular design, presenting pilotage imagery and aircraft status symbology via a miniature 1-inch diameter cathode-ray-tube (CRT). The pilotage imagery presented by the IHADSS originates from a forward-looking infrared (FLIR) thermal sensor mounted on the nose of the helicopter (Rash et al., 1998).

I^2 and thermal FLIR imagery offer the Army aviator uniquely different views of the outside world. An obvious approach for next generation of HMDs is to provide the aviator with the capacity to view both I^2 and FLIR imagery, either in alternation (via selective switching) or as fused imagery. While a host of optical issues must be addressed, any HMD design that wishes to explore this approach must still contend with the important biodynamic characteristics of head-supported weight and center-of-mass (CM).

In the past two decades, in an attempt to improve CM, several HMD designs have been developed that move the I^2 sensors from directly in front of the eyes to positions on the sides of the helmet. Other proposed designs have coupled this relocation of the I^2 sensors with the added capability of presenting FLIR imagery via miniature displays.


Figure 1. The I2-based ANVIS (left) and the AH-64 IHADSS (right) HMDs.

One perceptual consequence of an HMD design that relocates the I^2 tubes to the sides of the helmet is a phenomenon referred to as "hyperstereopsis," an informal term used for "hyperstereo vision." This phenomenon manifests itself as exaggerated depth perception, which is characterized by intermediate and near objects appearing closer than normal. At close distances, the ground appears to slope upward, creating a "crater" effect (figure 4). The limited number of studies investigating aviator performance and "adaptation" to hyperstereopsis have resulted in mixed findings.

The U.S. Marine Corps has selected, and is currently performing operational testing on, the TopOwl HMD, manufactured by Thales Visionics, France, for use in its Cobra AH-1Z helicopter. In anticipation of this, or a similar, hyperstereo design being considered for future U.S. Army aviation programs, the U.S. Army Aeromedical Laboratory (USAARL), Fort Rucker, Alabama, conducted a limited flight evaluation to assess the impact of hyperstereo on aviator visual performance during standard helicopter maneuvers and to identify issues that may need further investigation before such designs can be successfully fielded in the demanding Army rotary-wing environment.

Rather than pseudo-engineer a device to provide the hyperstereo effect, a decision was made to use the TopOwl HMD. It is one of a limited number of hyperstereo HMD designs currently in production.

Background

Rationale for a hyperstereo HMD design

In the 30-plus years that have followed the introduction of NVGs into Army aviation, a number of engineering advancements have improved greatly the resolution and sensitivity of these devices. The current version of ANVIS, using GEN III+ intensifier technology, is ubiquitous within the U.S. Army's helicopter fleet. ANVIS is a binocular system, providing a fully-overlapped, 40-degree field-of-view (FOV). The U.S. Navy, Air Force and Marine Corps field similar systems. Continuing research and development of I^2 technology has resulted in the capability of operating under no-moon starlight illumination and in the development of such promising systems as panoramic (wide FOV) and pseudo-color NVGs.

Resolution and sensitivity, two of the most important ANVIS operating parameters, have greatly improved from one generation to the next. However, the physical configuration of the ANVIS has not changed; the I^2 tubes are mounted in front of the eyes. Consequently, among the most consistent disadvantages of I^2-based systems are head-supported weight and center-of-mass (CM), critical parameters in the design of all HMDs. These parameters impact neck muscle fatigue, possible crash survivability, and user acceptance. In ANVIS and other aviation-fielded binocular I^2-based HMDs, an I^2 sensor (also serving as the image source) and its display are packaged together in each intensifier tube. The pair of intensifier tubes is placed forward and in front of the eyes, inherently creating a forward CM offset. Current Army ANVIS with associated battery pack are cited as adding an additional mass of approximately 0.91 kilogram (2

pounds) to the head-supported weight of the helmet (McLean et al., 1998). The common use of additional counterweights to offset the forward CM shift further increases head-supported weight (McLean et al., 1996). The issue of CM shift has been a strong driver for relocation of the I^2 tubes, resulting in the hyperstereo HMD designs. In addition, current ANVIS precludes the wearing of visors, a critical eye safety issue.

A more operationally significant driver has been the desire to provide an HMD design that integrates both I^2 and thermal FLIR imagery. In the development of the U.S. Army's AH-64 Apache, the thermal FLIR sensor was chosen over I^2 sensors and was located on the front of the aircraft. This left only the image source and optics to be mounted (integrated) into the HMD. At the time of IHADSS development (mid-1980s), the only viable choice of display technologies was the CRT. Even with the development of miniature CRTs, to overcome the weight, power requirement, and heat generation issues, the weight and volume of the CRT and relay optics forced the IHADSS into a monocular optical design.

In the IHADSS design, imagery is delivered only to the right eye. The pilot's left eye is not occluded and remains available for viewing either inside or outside the cockpit. Even with the decision of a monocular design, the largest size of the IHADSS helmet/HMD has a head-supported weight of approximately 4.1 pounds (1.86 kilograms).

The IHADSS optics are attached to the right side of the IHADSS helmet and impose a CM offset, slightly forward and to the right of the unencumbered head-neck CM. Although the IHADSS followed an integrated ground-up design approach, it also suffers from the classical HMD problems of excessive head-supported weight and shift in CM.

The two imaging technologies (I^2 and FLIR) offer aviators different spectral representations of the outside world. Each technology has a different physics principle of operation. The principle of I^2 is one of light amplification; FLIR operates on the principle of detecting small temperature differences based on the thermal emission (blackbody radiation) of objects (Rash et al., 1990). Not surprisingly, each technology has advantages and disadvantages. A "best of both worlds" philosophy would advocate a dual-sensor approach in future rotary-wing doctrine and HMD development programs. FLIR sensors cannot be located inside the cockpit since the 8-12 micron wavelength systems are attenuated by the aircraft windscreen materials. Mounting I^2 with a turret mounted FLIR and using a video linkage reduces resolution and contrast when compared to current and near-term I^2 systems with a direct optical linkage.

In summary, the current binocular I^2 HMD design of ANVIS, which is considered a necessity for military rotary-wing aviation nighttime operation, suffers from head-supported weight and CM problems. It is also advantageous to be able to provide alternately both high-resolution I^2 and FLIR imagery integrated into a single HMD. For this reason, it is necessary to pursue new and novel integrated HMD designs that reduce HMD head-supported weight and CM offset. One approach relocates the I^2 tubes to the sides of the helmet, introducing hyperstereo vision and its abnormal perceptual cues.

Past and present hyperstereo designs

There have been a limited, but surprising, number of HMD designs where the I^2 sensors were relocated, forming a configuration that resulted in hyperstereo vision. Sensor separation distances, and hence effective interpupillary distances (IPDs), have ranged from 102 mm (4 inches) to over 279 mm (11 inches), as opposed to the average eye separation of approximately 64 mm (2.5 inches). The majority of these designs, although having the support of strong developmental programs, never progressed to full production. Most of these systems were first developed for fixed-wing applications. Brief descriptions design examples follow:

- <u>The Tactical-Air Night Vision Display System</u>, built by Night Vision Corporation and commercially known as "Eagle Eye," was a low-profile, helmet-mounted, image intensifying system. It was a self-contained system, consisting of two GEN III I^2 tubes, folded optics beamsplitters, external housing, and integrated power supply. The folded optical path was designed to allow the I^2 sensors to be located slightly below and to the side of each eye, making the total separation between centers approximately 126 mm (5 inches). The effective IPD was approximately twice the normal 64-millimeter (mm). Like ANVIS, the nominal FOV was 40 degrees and fully overlapped. The objective lenses could be focused from 11 inches to infinity. While there was no eyepiece optical adjustment, eyepiece lenses could be inserted in two-diopter increments to compensate for spherical refractive error ranging from -6 to +2 diopter. Adjustments included fore-aft, vertical, tilt, and IPD. See figure 2 (top left). The Eagle Eye had a limited production in the 1980s.

- <u>The Knighthelm,</u> built by BAE Systems, Rochester, United Kingdom, was fielded on the German Tiger helicopter. It was a two-part design, using a form-fit helmet and an outer display module (White and Cameron, 2001). See figure 2 (top right). The design integrated I^2 and FLIR-based CRT imagery. It presented a 40-degree, fully-overlapped FOV. It provided a 15-mm exit pupil and a 30-mm eye relief. The interocular separation distance was not available, but is estimated to be between 250-280 mm (10-11 inches) based on photographs.

- <u>The Integrated Night Vision System (INVS)</u>, built by Honeywell, Inc., Minneapolis, Minnesota, and commercially known as the Monolithic Afocal Relay Combiner (MONARC), consisted of a helmet subsystem, a binocular image display system, and a provision for a magnetic head tracker. The helmet included a visor, energy liner, retention system, communications, thermoplastic liner, image display, magnetic receiver mounts, and electrical interfaces. Imagery, from *binocular* I^2 sensors and *biocular* CRTs, with added symbology was designed to be displayed through the imaging system which consisted of separate modules mounted to each side of the helmet. The modules were powered by an ANVIS-style battery pack. Each module contained a GEN III I^2 tube, CRT, objective and

Eagle Eye (Night Vision Corporation) Knighthelm (BAE)

MONARC (Honeywell)

TopOwl (Thales)

Figure 2. The Tactical-Air Night Vision Display System ("Eagle Eye") and Knighthelm (top); The Integrated Night Vision System (INVS/MONARC) (middle); and the TopOwl (bottom) (U.S. Army Aeromedical Research Laboratory).

relay optics, and beamsplitter. The I^2 sensors were located beside and slightly above the user's eye, making the total separation distance between sensors (and effective IPD) approximately 254 mm (10 inches) (4X normal IPD). The objective lenses could be focused from 6 meters to infinity. The vertical and lateral IPD positions of each module could be adjusted independently, but there was no fore-aft or tilt adjustments. This system provided a nominal 35-degree, fully overlapped FOV. See figure 2 (middle). The INVIS program actually had several designs under contract. See Gunderman and Stiffler (1992) for full descriptions.

- The TopOwl is manufactured by Thales, France. It has a fully-overlapped, 40-degree FOV visor projection system, capable of presenting both I^2 and FLIR imagery. The visor projection approach eliminates the requirement for optical beamsplitters and increases physical eye relief to >70 mm (>2.75 inches). Dual I^2 sensors are located on the sides of the helmet with a separation distance of approximately 286 mm (an effective IPD of more than 4X normal). The I^2 imagery is optically-coupled to the visor. The FLIR imagery from a nose-mounted thermal sensor is reproduced on miniature CRTs and projected on to the visor. TopOwl does not provide fore-aft, tilt, or IPD adjustments. See figure 2 (bottom). TopOwl HMDs are in full production with over 400 fielded or being evaluated in 15 countries (Cloue et al., 2008).

This synopis is not intended to be exhaustive. For reference, other systems not described, but have also presented hyperstereo imagery, include the Crusader and the EF2000, both developed by Marconi Avionics (now BAE Systems), United Kingdom, and the Modular Integrated Display and Sight Helmet (MIDASH), built by Elbit Systems, Israel.

Hyperstereo vision

The average IPD for U. S. Army males is 64 mm and 61 mm for females (Donelson and Gordon, 1991). Because the eyes are at different positions, each eye has a slightly different view of the outside world (perspective). This results in two slightly different retinal images in the two eyes for relatively near objects. It is this retinal disparity that allows humans to perceive these objects as three-dimensional. This image disparity is called stereopsis. Humans generally do not notice depth in objects that are more than a few hundred feet away. This is because at this distance and beyond, the rays arriving at the eyes are essentially parallel, and the retinal disparity and binocular object perspective cues become too small to resolve.

Stereopsis is an important binocular cue to depth perception, which provides the ability to estimate absolute distances between ourselves and an object, as well as the relative distances between two objects, i.e., which is closer. However, depth perception does not require stereopsis. Multiple visual cues are used to define our sense of depth. Both differences and similarities between two retinal images are fused and compared within the brain to produce depth perception (Hill, 2004). The cues for depth perception also may be monocular. Monocular cues include:

- Relative size
- Interposition
- Geometric perspective
- Contours
- Shading and shadows
- Monocular motion parallax

Interpupillary distance defines the separation between the two retinal images and ranges from 57 to 72 mm (1^{st}-99^{th} percentile male) and has an average of 64 mm. In artificial situations where the input sources are located at greater than normal IPD, a condition called hyperstereo exists. A number of terms have also been applied to this visual condition, e.g., hyperstereopsis, tele-stereo, enhanced-stereo, etc. [Note: In many stereo contexts, the separation between the (sources of the) inputs to the two eyes is referred to as the stereo baseline (distance).]

The effect of greater-than-normal separation of the inputs to the two eyes produces very complicated and varied results that depend on the amount of separation and the point of fixation. For example, a pilot usually will perceive the near ground as if rising up to him/her. When a helicopter pilot is sitting on the ground, it may seem that ground level outside the cockpit is at chest level, causing some pilots to say it looks like they are sitting in a hole. However, distant objects may look natural (figure 4).

It follows from an analysis of the geometry that when greater-than-normal separation of inputs to the two eyes exists, the retinal disparity with respect to the target position or the convergence angle to an object being viewed can be increased (figure 3). This may cause the apparent distance to a viewed object to appear shorter, an observation confirmed by pilots using a hyperstereo HMD. However, there is some controversy regarding the role convergence has in distance estimation (Brenner and Van Damme, 1998). As depicted in figure 3, the difference in perceived distance, due to increased retinal disparity (exaggerated stereoscopic depth perception/increased differential perspective) may, at near viewing distances, also be due to a change of convergence angle. For a normal interocular separation distance (i.e., IPD), the fixation point located at distance D subtends an angle α**.** For the increased separation distance depicted for the I^2 tubes in this diagram, the convergence angle increases to β (top of diagram) and retinal disparities between the fixation point and imaged objects in the field-of-view (FOV) increase. However, the visual system may still operate from the "assumption" of a normal IPD. As a consequence, the apparent convergence angle of β (bottom of diagram) causes the target object's distance to be perceived as D'; D' < D, hence the target object appears closer. The object size will appear to be approximately the same at both D and D', giving the impression that the object is smaller.

In addition to objects appearing closer, another manifestation of hyperstereo is the ground appearing to slope upward, toward the observer, creating what is often described as a "bowl" or "dish" effect (figure 4). The observer describes the ground nearest to him as appearing closer (higher); this exaggerated depth effect decreases with distance away from the observer. When the helicopter is on the ground, the pilot may perceive the near ground as being at chest level,

while distant objects look natural. This decreasing effect with distance corresponds with the pilot's decreasing ability to evaluate decreasing angular perspective effects.

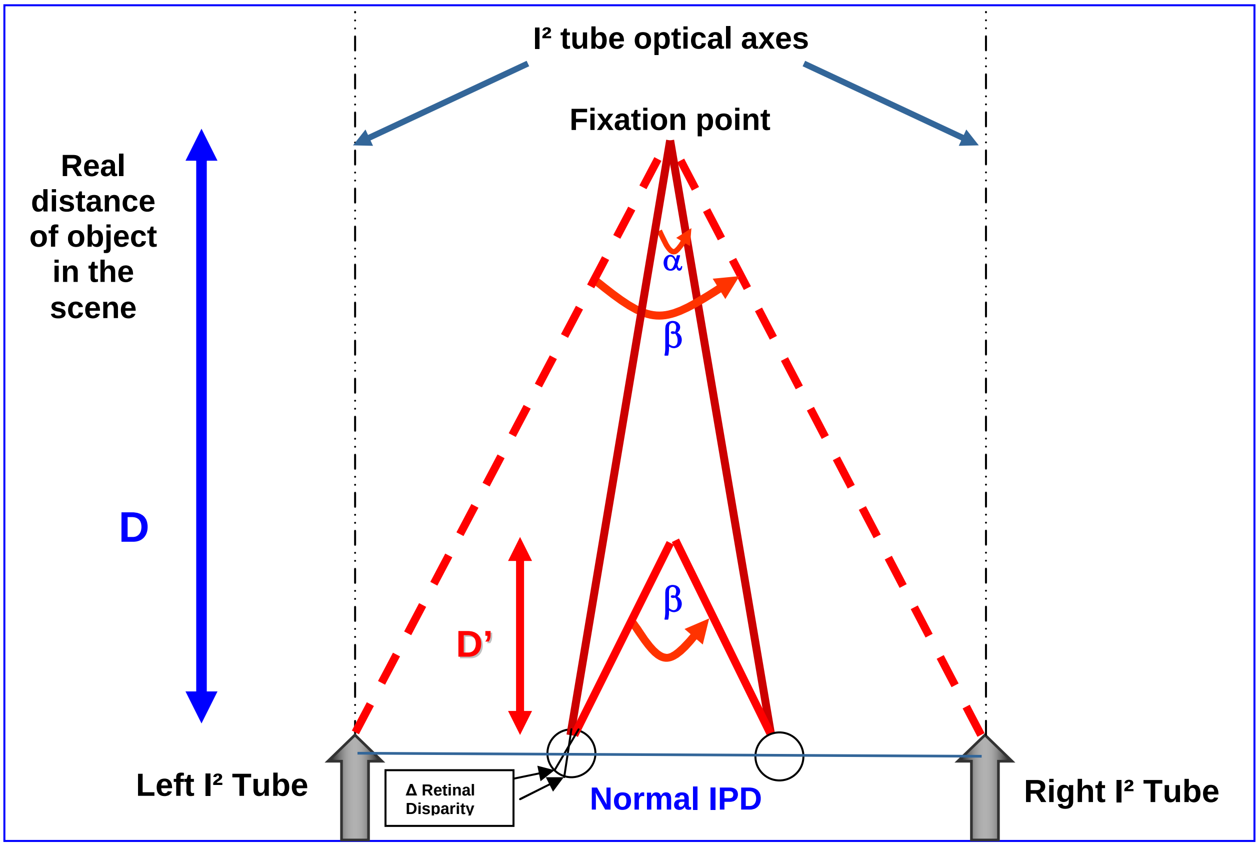


Figure 3. Diagram depicting change in perceived distance due to hyperstereo.

Note: Previous version is inaccurate. Pilots see themselves and the aircraft as sitting in the ground when on the ground. The near ground appears to rise up to chest level. Beyond 50-200 feet the ground appears normal (to level off). The experience is not like sitting on top of a volcano.

Figure 4. Wire depiction of near ground rising up to chest level, creating the "crater" illusion arising from hyperstereo viewing.

It should be noted that hyperstereo results from an increased effective IPD and not from a proportional increase in the vertical dimension subtended by an object. The proportional angular impact of convergence decreases with distance, consequently making the apparent relative horizontal and vertical dimension of objects appear relatively more normal (figure 4). A dynamic aspect of this selective horizontal, but not vertical distortion that can also impact hyperstereo HMD user performance is the change in velocity and acceleration vectors with object angle of motion. How the brain interprets this and how it may adapt to this condition is not entirely clear. However, the potential impact on critical performance in a dynamic world is clear enough.

Hyperstereo is largely, although not entirely, a near effect that is usually manifested within a few hundred feet. A good-rule-of-thumb is that when the perspective differences of an object falls below one minute of arc, the impact of hyperstereo becomes negligible, and competing monocular depth cues become dominant.

The preceding narrative is a superficial description of stereo vision and the special condition of hyperstereo. It is intended only to provide the background necessary to understand the data collected and discussed in later sections. The concept of hyperstereo from a vision science perspective is a significantly more complicated topic. A more in-depth discussion would include rivalry of the retinal images and the potential impact of optical differences on hyperstereo effects (e.g., prism, binocular parallax, optical distortion, velocity and acceleration effects, etc.). Priot et al. (2006) provide an excellent review of the hyperstereo (hyperstereopsis) literature from an operational perspective.

Thus far, hyperstereo has been described as a negative attribute. However, some atypical hyperstereo configurations (based on camera pairs with extremely wide baselines or temporal delays with a single camera) have been investigated for their possible use in aerial search and rescue, target detection, and traversing drop-off terrain tasks (e.g., Cheung and Milgram, 2000; Schneider and Moraglia, 1994; Watkins 1997).

Studies evaluating hyperstereo vision

HMD designs with hyperstereo are not new. They date at least to the mid-1980s. The U.S. military have evaluated and conducted studies on several proposed designs. Additional studies have investigated the potential advantages of hyperstereo. The following is a synopsis of the more relevant studies and papers pertinent to this report:

- In 1990, the National Aeronautics and Space Administration (NASA) investigated hyperstereo for its potential use in improving hover-in-turbulence performance in rotorcraft (Parrish and Williams, 1990). While objective measures demonstrated some improvement in situation awareness, decreased control activity, and hover stability, it was subjectively disliked by the pilots because of the exaggerated visual cues experienced.

- In 1992, the Night Vision Laboratory (currently Night Vision and Electronic Sensor Directorate), Fort Belvior, Virginia, conducted an evaluation of the potential use of the Honeywell INVS/MONARC HMD in helicopters. The INVS was being developed in an attempt to design a night vision I^2 system with lower weight and improved center of mass for fixed-wing aircraft. The objective lenses and intensifier tubes were placed on the side of the helmet with a separation approximately 4 times that of normal IPD, introducing the condition of hyperstereo. The study's objective was to compare aviator performance with INVS to performance with ANVIS. On initial concept flights in a TH-1 helicopter (modified AH-1S Surrogate trainer), pilots found the hyperstereopsis and sensor placement on the sides of the helmet to be major deficiencies during terrain flight. The vertical supports in the canopy always seemed to be within the FOV with any head movement, and under starlight conditions, the pilots rated the hyperstereo system unsafe and terminated the study except for demonstration rides (Kimberly and Mueck, 1992). The reported hyperstereo effects were characterized by intermediate and near objects appearing distorted and closer than normal. The ground was reported as appearing to slope upwards toward the observer and regions beneath the aircraft appearing closer than normal. Safety pilots noted a tendency to fly higher than normal during terrain flight.

- In 1992, the U.S. Air Force also conducted testing on potential ejection-safe HMD designs that demonstrated the hyperstereo effect under the Interim-Night Integrated Goggle Head Tracking System (I-NIGHTS) program (Grove, 1992; Gunderman and Stiffler, 1992). I-NIGHTS began as a joint Air Force/Navy development with the Navy as the designated lead. Candidate systems were designed by Kaiser Electronics, Honeywell (same as MONARC) and GEC Avionics). All three designs placed the I^2 tubes at greater than normal IPD. Flights were conducted in the HC-130 (fixed-wing) and MH-53 and MH-60 helicopters. Interestingly, the final reports do not provide either the I^2 separation distances for the HMDs or subject pilot IPDs. The hyperstereo effect apparently was not anticipated, as the flight performance evaluation questionnaire did not specifically ask about this effect, asking only one generalized question regarding image distortions. However, within individual comments, the helicopter pilots reported that the Kaiser HMD "slightly magnified images, creating the illusion of being lower than actual altitude. This became very apparent during landing where the pilot anticipated touchdown at the any moment while he was actually still 3-4 feet in the air."

- In 1993, in support of the development of the Helmet Integrated Display Sight System (HIDSS) HMD for the U.S. Army's RAH-66 Comanche helicopter, the USAARL and the U.S. Army Aviation and Technical Test Center (ATTC), Fort Rucker, Alabama, conducted a flight study which included an investigation of the effects of hyperstereopsis on aviator performance (Armbrust, 1993). Eight subject aviators flew 150.5 flight hours in an AH-64 Apache. Subjects performed a series of six modified ADS-33C (U.S. Army, 1989) maneuvers while wearing the ANVIS, Eagle Eye, and MONARC HMDs. These three systems represented IPD

ratios (to normal) of 1X, 2X, and 4X, respectively. The effect of hyperstereo viewing on aviator performance was evaluated through the collection of quantitative (i.e., accuracy of hover, drift and heading) and subjective measures (i.e., Subjective Workload Assessment Technique [SWAT], Perceptual Task Rating Scale [PTRS], and Subjective Performance Rating Scale [SPRS]). The study concluded that the effects of hyperstereo were minimal. It was stated that aviators "learned compensation strategies quickly." However, it was noted that performance involving altitude estimation was affected to a greater extent. Overall, none of the subjective measures showed any difference in workload associated with the three systems. However, for low level tasks, data did show that the two hyperstereo HMDs were more difficult to fly than ANVIS. [Note: One of the authors was a participant in the joint ATTC/USAARL study summarized herein. In his opinion, the reported findings did not fully capture the impact of hyperstereo on aviator performance. First, due to logistical issues, the flights were conducted under extremely benign conditions and at locations that provided too many overriding cues. Second, the AH-64 aircraft provides the least forward looking vision of any U.S. Army aircraft. This inability to look forward circumvented the potential of the pilots to accurately assess the hyperstereo effects. Third, a thorough review of recorded pilot comments frequently included the perception of "landing in a hole" and having to "feel for the ground." In addition, safety pilots noted that subjects were consistently flying higher than required during terrain flight and had greater difficulty with aircraft drift. Fourth, there were reports that switching to and from a hyperstereo view was a problem. These issues were noted in the original report, but were not fully presented in the summary findings.]

- In 1995-1996, Leger et al. (1998) conducted a two-phase flight test of an earlier configuration of the current TopOwl HMD, i.e., visor projection and 40-degree, fully-overlapped FOV. Sixty-six hours were flown in Phase One (40 hours at night; 77 flight hours were accumulated in Phase Two (45 hours at night). While various platforms were used, most of the evaluation was conducted on a SA 330 (Puma) test-bed platform developed for the TIGER program. The interocular separation was 240 mm, 46 mm less than that of the current TopOwl version, and was approximately 4X normal IPD. The independent variables in the study were distance and height above the ground. The study reported "a systematic under-estimation of distance and height, (with) pilots feeling closer and lower than they really were." Pilots were reported to have "returned to nominal performance" after 5 to 10 hours of flight.

- In 1998, two German test reports documented flight experience with two hyperstereo HMD designs, the Knighthelm and the TopOwl (Hohne, 1998; German Air Force Test Center [WTD], 1998; in Priot et al., 2006). Both evaluations reported altitude evaluation errors. A later German evaluation of just the TopOwl concluded that: "The approximately double base distance of the objective lens[es] in relation to the eye creates a false range feeling during hover flight when

evaluating the aircraft altitude. The impression gained is one of a low hovering altitude" (Krass and Kolletzki, 2001). In all three evaluations, pilots reported the ability to compensate after relatively few flight hours.

- In 2001, the U.S. Army Research Laboratory, Aberdeen Proving Ground, Maryland, conducted a study on the effects of hyperstereo viewpoint offsets of NVGs on accuracy in a simulated grenade-throwing ground task (CuQlock-Knopp et al., 2001). In the study, 32 National Guardsmen were tasked with throwing simulated grenades onto a trap-door target located 20 feet away. The measured data were the radial direction and distance from the target for each toss. Three viewpoint (hyperstereo) configurations (figure 5) were compared to the normal IPD ANVIS. Only two of the three configurations presented a horizontal displacement; the third presented a vertical displacement only. The two horizontal hyperstereo distances were approximately 6.7 and 8.5 inches (170 and 216 mm), both equating to approximately 3X normal IPD. The results of the study showed that the hyperstereo resulted in a statistically significant increase in the magnitude and direction of the throwing errors.

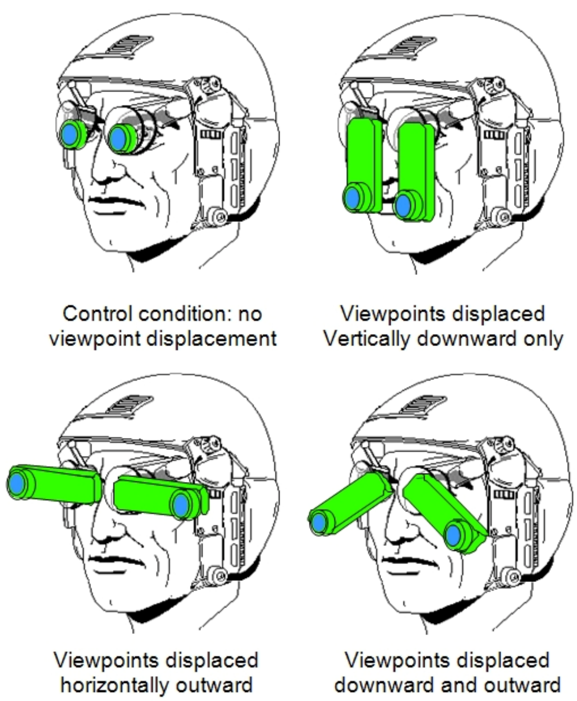


Figure 5. An artist's rendition of the four viewpoints used in a simulated grenade-throwing task study (CuQlock-Knopp et al. 2001).

In summary, hyperstereo HMD designs offer a significantly improved CM and significantly reduced optical pathway interference, while retaining the advantages of helmet-mounted I^2, which include improved resolution over all current night vision cameras. This being said, hyperstereo HMD designs introduce visual distortions. Finding out which of these are visually

significant for pilots is the purpose of this study. Ultimately, this information will need to be evaluated for impact on actual static and dynamic performance.

Methodology

Subjects

A total of five subjects participated in this flight evaluation using the TopOwl HMD. Two subjects (#1-2) flew a total of 8 hours each (four 2-hour flights); three subjects (#3-5) flew a single 1-hour flight. All subjects were rated U.S. Army UH-60 qualified aviators. Median age was 40 years. Total NVG flight hours ranged from 150 to 1100. A summary of subject demographics is provided in table 1. An important note is that the subjects did not at any time take controls of the aircraft. Subjects occupied the left seat of the aircraft; the safety pilot, on controls at all times, was seated in the right seat.

All subjects were briefed on the purpose, procedures, risks and benefits of this study. There questions about this study were encouraged and answered. They were informed that they could stop participation in this study at any time for any reason without repercussions. All subjects signed an informed consent prior to participation in this study.

Equipment

All flights were conducted in USAARL's JUH-60 Black Hawk research helicopter (figure 6). The hyperstereo HMD employed was the Thales Avionics TopOwl described above. All flights (except one) were flown under a low moon illumination (<25%) (table 1).

Table 1.
Subject demographics.

	8-hour subjects		**1-hour subjects**		
	#1	**#2**	**#3**	**#4**	**#5**
Age (years)	34	41	34	30	42
Total NVG hours	150	800	600	155	1100
Use of vision correction	No	No	No	No	No
IPD (mm)	67	61	63	63	65
% moon illumination	100/0/0/0 - 0/0/0/0		15	25	25

Figure 6. USAARL's JUH-60 Black Hawk helicopter.

The Armed Forces Vision Tester (AFVT) was used to perform pre/post-flight stereo and phoria vision tests. This tester or an equivalent is used for military visual assessment for all types of physical examinations. The AFVT is a semiportable machine that has the capability to test near and distant visual acuity, horizontal and vertical phorias, and stereopsis (depth perception). It consists of two rotating drums that hold illuminated slides. The handles on the side of the machine rotate the drums to select the slide for the selected test. For this study, only test slides for distance stereopsis, distant vertical and lateral phoria, and near lateral phoria were used.

Questionnaires

Three questionnaires were used to capture subject self-evaluation of their ability to perform standard flight maneuvers with a hyperstereo HMD design and, based on their previous flight experience with ANVIS, to compare their performance to that with standard ANVIS. The first questionnaire, titled "Post-flight hyperstereopsis questionnaire," was completed by each subject following each flight (i.e., subjects #1-2 after each 2-hour flight, subjects #3-5 after the single 1-hour flight) (appendix A). The objective of this questionnaire was to capture subject experiences with the hyperstereo effect. Questions also addressed flight performance issues and comparisons of operating characteristics between the hyperstereo device and standard ANVIS (e.g., distortion, low light gain, halo size, etc.). Subjects also were requested to provide their assessment of both the advantages and disadvantages of a hyperstereo HMD design.

A second questionnaire, titled "ANVIS/Hyperstereo HMD comparison questionnaire," was distributed to all subjects following their last flight (appendix B). For subject #1-2, this was after 8 hours of flight; for subject #3-5, this was following their single 1-hour flight. The questionnaire required subjects to compare their ability to perform maneuvers with the hyperstereo device to their ability with ANVIS. This was achieved using a 5-rank Likert scale, where 1 indicated "much better than with ANVIS" and 5 indicated "much worse than with ANVIS." The neutral rank of 3 indicated "same as with ANVIS." Subjects were asked to provide a similar rank for all maneuvers as a whole under both low and high light conditions. Additional comments were solicited.

The final questionnaire, titled "In-flight interview questionnaire," was administered by a technician seated directly behind the safety pilot (appendix C). Following the completion of each flight maneuver, the technician asked the subject a series of questions that, while varying somewhat between maneuvers, basically addressed the ability to judge height above the ground, the presence of image distortion, the detection and control of aircraft drift, and changes in head scanning method resulting from the use of the hyperstereo HMD or aircraft windscreen support structures blocking outside vision. Subject responses to the interview questions were recorded on an audio channel for later transcription. Unsolicited subject comments and safety pilot feedback (e.g., true altitude readings following subject estimations) also were recorded.

Procedures

On the afternoon of a first flight, the subject was requested to come to the USAARL for a helmet fitting, a TopOwl training briefing, and a flight safety briefing. The TopOwl HMD uses a custom-fit helmet system that is achieved through the laser scanning of the wearers head and subsequent manufacturing of a form-fit helmet interior. This technique is designed to ensure and maintain a proper match between the entrance pupils of the wearer's eyes and the exit pupils of the HMD optics. This requirement addresses a well-documented problem between the size and shape of the HMD exit pupil(s), physical eye relief, allowing a full FOV without vignetting (Rash et al., 2002). Due to time and travel constraints, subject availability, and local unavailability of the laser head-scanning system, subjects were fit using a pad system and five different sized foam liners by a USAARL technician that had been trained by a Thales Avionics representative. Prior to flight, a final check on the fit of the helmet and the subject's ability to achieve a full FOV was conducted (figure 7).

Following the helmet fitting, each subject was provided a training briefing on the study. The briefing was based on a training package provided by Thales Avionics and modified for the purpose of this evaluation. It provided a brief tutorial on the concept of hyperstereopsis, the objectives of the evaluation flights, the operation of the TopOwl HMD including available adjustments, and a list of the types of perceptual effects that might be encountered while using TopOwl. This briefing was given only once for each subject. Questions were encouraged and answered by the researchers, technicians, or safety pilot.

Figure 7. Final adjustment of TopOwl HMD on subject pilot.

The training briefing was followed by a flight briefing that outlined the maneuvers to be flown, briefed the local weather forecast, outlined the flight path, and reviewed safety procedures. Subjects then were released and asked to report at the airfield at least one hour prior to aircraft launch.

Once all personnel had assembled at the airfield, a final crew briefing was held, which reiterated the flight goals, flight procedures, and safety issues. The subject was then pre-tested for stereopsis and phoria using the selected slides in the AFVT housed in a van adjacent to the launch pad. This testing required approximately 5 minutes. The subject then was allowed to don the TopOwl and instructed to walk around the general area of the aircraft in order to gain familiarity with the hyperstereo effect. This familiarization period was approximately 10-15 minutes in duration. Subjects also observed from an aircraft service platform, which was approximately 6 feet above the ground, overlooking the airfield.

Following the above activities and after flight clearance was given, the safety pilot initiated the flight and began the sequence of the 13 selected maneuvers. (See following section, “Flight maneuvers.”) During each flight (two for subject #1-2 and one each for subjects #3-5), the 13 maneuvers were performed by the safety pilot. At the end of each maneuver, the technician asked the subject the designated questions from the “In-flight interview questionnaire.” At the end of the flight (within 10 minutes from touchdown), the subject moved to the adjacent van and repeated the AFVT tests. The subject then completed the “Post-flight hyperstereopsis questionnaire.” For subject #3-5 and on the last flights of subject #1-2, each subject completed the ANVIS/Hyperstereo HMD comparison questionnaire. Following an after-flight debriefing, the subject then was released.

Flight maneuvers

A series of 13 flight maneuvers was used in the evaluation. The approximate flight time to complete all 13 was one hour. The maneuvers (table 2) were initiated from, and ended at, Lowe Army Air Field, Fort Rucker, Alabama. The maneuvers were selected based on their

Table 2.
Flight maneuvers.

1- In-ground-effect (IGE) hover and land to ground (repeated 3 times)
2- Visual Meteorological Conditions (VMC) takeoff
3- Straight and level flight @ 100 feet above highest obstacle (AHO)
4- VMC approach to a 10-foot hover
5- Slope landing and takeoff to a hover
6- IGE Hover @ 10 feet with 360° pedal turns
7- VMC takeoff
8- VMC approach to the ground
9- VMC takeoff into traffic pattern
10- Roll-on landing
11- Back taxi on runway, 50-foot deceleration
12- VMC takeoff and return
13- Roll-on landing

representation of those typically and routinely performed by U.S. Army aviators and those that might be affected by the presence of hyperstereo. A full description of the maneuvers is provided in appendix D. During all phases of flight, the safety pilot was on the controls, and the subject wearing the TopOwl HMD only observed and conducted copilot duties.

Laboratory evaluation

Since the TopOwl HMD was the device selected to produce the hyperstereo effects during flight, it was essential to characterize its operational I^2 tube and optical performance. This characterization was necessary for three reasons. First, for safety of flight considerations, the system's collimation error and performance under both low- and high-light conditions needed to be verified as meeting or exceeding Army qualification specifications for ANVIS (Department of Defense, 1992). Second, adequate subject selection to ensure the ability to achieve a full FOV depended on knowing the acceptable IPD range of the TopOwl. Lastly, having available a full characterization of the system's operating parameters might be useful in explaining study findings on flight performance.

In addition, virtually all I^2 night vision devices used in the military are non-exit pupil forming systems. The pupil-forming design of the TopOwl provided an opportunity to develop techniques for measuring image characteristics of an I^2 pupil-forming system that may be useful in evaluating similar future designs. For this reason, appendix E provides a more detailed

documentation of the laboratory assessment methodology that includes some modified measurement techniques.

Note that the TopOwl is a Class B I^2 system. The system Class designation refers to the choice of a spectral cut-off filter coating used on the objective lenses. Because of the Class B designation, it was decided to compare performance to a F4949 I^2 system, one used by the U.S. Air Force, Navy and Marine Corps, rather than to the U.S. Army ANVIS, which is a Class A device.

A list of laboratory assessment system parameters is provided in table 3. For proprietary concerns, actual measured values for many of the test parameters are not cited here. However, their success or failure in meeting the performance of the F4949 I^2 system used for comparison is noted. For most of the operating characteristics, the performance of the TopOwl matched or exceeded those of the F4949. One parameter for which performance greatly exceeded that of the F4949 was physical eye relief. This was measured to be approximately 72 mm.

The parameters of greatest concern were those associated with exit pupil size and IPD range. The TopOwl was measured to have a 12-mm vertical by 16-mm horizontal exit pupil (figure 8) and a fixed IPD setting of 65 mm. This combination, in the opinion of the authors, will restrict the obtainment of a non-vignetted FOV to users having an IPD range of 61 to 69 mm. This range is somewhat restricted as compared to the 52 to 72 mm range provided by the F4949. Based upon Donelson and Gordon (1991), the predicted fittable IPD range of 61 to 69 mm would accommodate, without vignetting, approximately 65% of males and 58% of female U.S. Army personnel.

In addition to the physical measurements performed, two physiological-based measures were made using experienced technical observers. These two measures were visual acuity (VA) under both high- and low-light conditions and subjective system response and recovery times to flashes of light. The TopOwl provided essentially the same high- and low-light resolution as the F4949 system. For high-light performance with the 1951 U.S. Air Force tri-bar resolution target chart, the measured Snellen visual acuity was only one resolution step lower than what was observed using the F4949. While a very small difference, this was not unexpected, as I^2 tube selection for the TopOwl HMD provided for this evaluation was restricted due to export control laws.

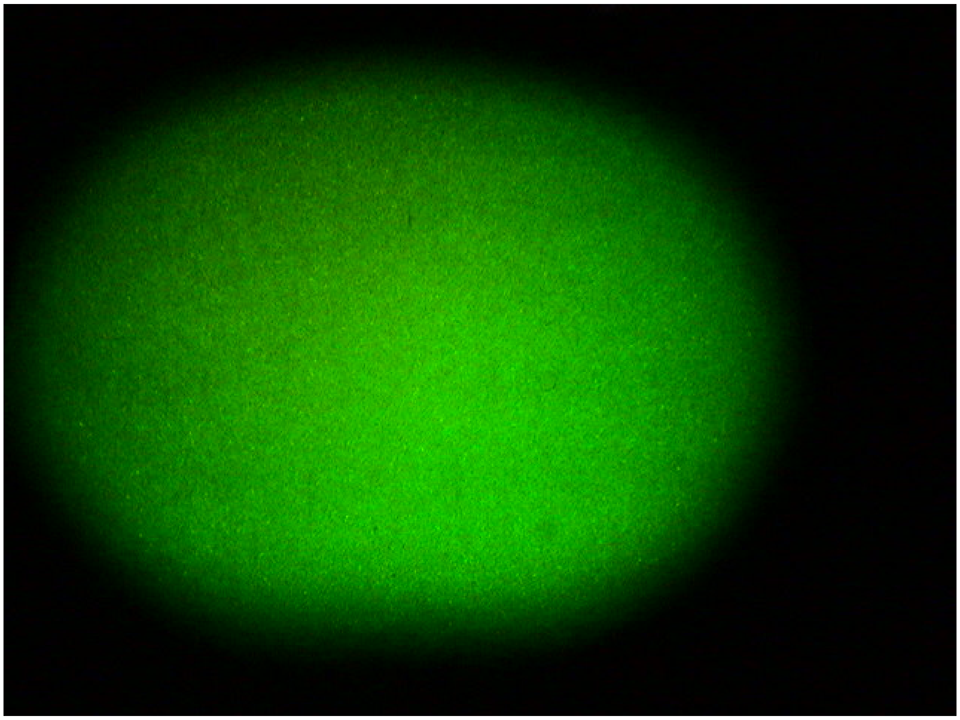


Figure 8. Shape of TopOwl exit pupil.

Table 3.
Summary of laboratory assessment of physical measurements.

Characteristic	Acceptable	Top Owl		F4949	
Halo size (millimeters on I^2 tube)	Yes				
Luminous gain	Yes				
Max Luminance	Yes				
CIE chromaticity coordinates	Yes				
Exit pupil size (via mechanical method)	Unknown	12-mm vertical; 16-mm horizontal		Not pupil forming	
Exit pupil size (no vignetting with CCD camera, 5-mm pupil)	Unknown	6-mm vertical; 10-mm horizontal		N/A	
IPD setting	Unknown	65 mm		52-72 mm; independent adjustments	
IPD range (with eye movement)	Unknown	61 to 69 just noticing vignetting		52 to 72 mm	
Physical eye relief (from visor)	Yes	~ 72 mm, visor tilts (pantoscopic)		~ 30 mm from eyepiece	
Eyepiece diopter setting	Yes	-0.25 diopter each optic		+2 to -6 diopters	
Collimation	Yes	No measurable deviation		Within MIL-A-49425(CR) requirements	
Response and recovery times (subjective measure)	Yes				
Intensified image distortion	Yes	None detected		None detected	
Current drain	Yes				
High-light resolution (Snellen)	Yes	20/28 (Right)	20/31 (Left)	20/25 (Right)	20/25 (Left)
Low-light resolution (Snellen)	Yes	20/89 (Right)	20/89 (Left)	20/79 (Right)	20/89 (Left)

Table 4.
TopOwl visor characteristics.

Parameter	**Measurements**		**Specification**	**Acceptable**
Transmittance	55% photopic; 67% scotopic		No specification	Yes
Refractive power	< 0.12 diopter, typically -0.08 sphere		≤+/- 0.125 any meridian	Yes
Distortion (MIL-STD-43511C)	Patterns 1-2		Pattern 1-5	Yes
Prismatic deviation (as worn at center) - Horizontal	Right 0.10 Base Out	Left 0.07 Base Out	Sum ≤ 0.18 BI ≤ 0.50 BO	Yes
Prismatic deviation (as worn at center) - Vertical	Right 0.40 Base Down	Left 0.44 Base Down	≤0.18 prism diopter	**No**

Pre/Post-flight vision test results

There were no systematic changes in pre-and post-flight measurements for either of the AFVT stereo or phoria vision tests. Measured values are provided in table 5. Subject #2 missed two more levels of the stereo targets in a post-flight measurement (as compared to pre-flight), but this was most likely caused by general fatigue and not a consequence of the hyperstereo HMD. A couple of the phorias were found to have changed by a small amount. For one subject, this change was towards esophoria one night and towards exophoria on another night. These small differences could be attributed to visual fatigue, small differences in accommodation, or normal physiological individual measurement variability.

Post-flight hyperstereopsis questionnaire data

This questionnaire was completed after each flight. Subject #1-2 completed this questionnaire each night following two hours of flight; subject #3-5 completed this questionnaire once following their single 1-hour flight. Due to the limited sample size, statistical analyses were deemed not appropriate. Instead the data are presented and examined using two approaches. The first approach examines responses for all subjects following the initial flight. The second approach presents the time-series response data for subject #1-2 only, over four nights (i.e., 8 flight hours).

> Note: It has been demonstrated that type and magnitude of phoria is sensitive to the optics being used (e.g., design, focus, FOV) and length of time the optics are used. Changes also result during the day from monitor use alone. In general, phoria changes back to a set value after rest, as in the morning. Small differences do not usually result in discomfort or reduced performance unless there is a vergence or accommodation problem. Visual fatigue is not a good phrase. However, I don't know a good one to describe these common changes.

Table 5.
AFVT pre/post-flight stereo (target levels) and phoria (prism diopters) vision test results.

AFVT parameters	Distant Stereo Difference	Distant Vert Phoria Difference	Distant Lateral Phoria Difference	Near Lateral Phoria Difference
Subject # 1 (Mean)	0	-0.25	0.5	1.5
Subject # 2 (Mean)	-0.25	-0.45	0.25	2.25*
Subject # 3	-2*	0	0	0
Subject # 4	0	0	0	0
Subject # 5	0	0	0	-1

*Considered to be attributed to instrument and/or display exposure duration.

Initial flight data

For subject #1-2, these data were collected following their first 2-hour flight; for subject #3-5, these data were collected following their first and only 1-hour flight. Tables providing these data are found in appendix F.

None of the subjects reported a difference in resolution between right and left tubes (Question #1) or the presence of image blur or flicker (Question #9). Not surprisingly, all subjects noticed a difference in depth perception when using the HMD with side-mounted I^2 tubes (Question #3). Comparing TopOwl to ANVIS, only one of the five subjects reported a difference when viewing instruments inside the cockpit or viewing outside the cockpit with unaided vision while using the devices (Question #8). One individual reported reduced eye strain immediately after removing the TopOwl (Question #18).

Three subjects (60%) reported the presence of ghost images due to reflections (Question #2) and multiple images (due to both a see-through and I^2 image of the same object) (Question #14). Two subjects (40%) reported a dimming of the image toward the outer edges of the FOV (Question #6). Four subjects (80%) experienced vision interference due to the aircraft structure (Question #16) and had difficulty in both up- and down-sloping terrain (Question #4). All subjects expressed the opinion that a training approach different from current NVG training would be necessary for both new NVG students and qualified NVG aviators (Question #12). Subjects 1-4 reported eyestrain; Subject 1 reported that tight helmet fitting caused pain and hot spots to form toward end of flight; Subject 2 reported scan-related neck pain (Question #5).

One question (Question #7) was rather extensive, asking subjects to compare TopOwl with ANVIS. It addressed primarily physical characteristics (e.g., halo size and intensity, distortion, etc.) but also inquired about depth perception and helmet stability, as well as recognized disadvantages and advantages. A summary of this comparison is provided in table 6.

Responses to Question #7 show the major problem to be depth perception. Two of the three subjects who provided a comparison rank of 5 (Much worse than ANVIS) cited difficulty in determining hover height. Parameters of head supported weight, CM, and unaided visual field had median reported ranks of 2 (Slightly better than ANVIS).

Questions #10-11 asked subjects to identify features of the TopOwl HMD that they considered to be either advantages or disadvantages (table 6). The most frequently cited advantage was reduced weight. There was no agreement among disadvantages provided but included (poor) depth perception, ghost images, and a negative impact on cross cockpit scanning.

Table 6.
Initial flight responses for comparison of physical characteristics of TopOwl and ANVIS.

Question #7 **Compare TopOwl and ANVIS for:** 1- Much better then ANVIS 2- Slightly better than ANVIS 3- Same as ANVIS 4- Slightly worse than ANVIS 5- Much worse than ANVIS	**Subject #1**	**Subject #2**	**Subject #3**	**Subject #4**	**Subject #5**	**Median**
Depth perception	**5**	**5**	4	**5**	4	**5**
Distortion	-	3	**5**	3	3	3
Bright light recovery	3	3	3	-	**5**	3
Tube brightness	2	4	3	4	4	4
High light resolution	1	3	3	NR	**5**	3
Low light resolution	NR	3	4	3	4	3.5
Halo size	3	**5**	3	2	**5**	3
Halo intensity	3	4	3	3	4	3
Head supported weight	4	2	2	1	2	2
Center of mass	1	2	2	1	4	2
Unaided visual field	1	2	3	**5**	1	2
I^2 Field of view	1	4	4	4	3	4
Helmet stability	1	3	3	2	4	3

In Question #13a, subjects were asked to rank their agreement with the statement, "By the end of the 50-minute flight, I was able to fully adapt to the hyperstereo visual effects," using a scale of 1-Strongly agree, 2-Somewhat agree, 3-Neither agree nor disagree, 4-Somewhat disagree, 5-Strongly disagree. Four subjects provided a "5-Strongly disagree" rank; the remaining subject provided a "4-Somewhat disagree" rank. This question also asked the subjects to give an estimate of "How many hours do you feel you will need to become proficient in flight performance? (i.e., reasonably adapted to the hyperstereo effects)" To which, only three subjects provided an estimate: 5, 6, and 15 hours. See appendix F for individual subject responses to the post-flight questionnaire for initial flights.

Table 7.
Reported advantages and disadvantages of TopOwl based on initial flights.

Subject	**Advantages**	**Disadvantages**
#1	Visual field; stability	Eyestrain
#2	Being able to see through to instruments	No FOV adjustments;* inability to use chin-bubble
#3	None	Ghost images; poor cross cockpit scanning
#4	Weight and center-of-mass	Depth perception
#5	Weight; better clearance from obstacles in the cockpit	Restricted visibility outside of cockpit

*This response was most likely referring to the absence of tilt and/or IPD adjustment.

Time series data

These data are for subject #1-2 and represent responses provided via four post-flight questionnaires, one completed after each nightly 2-hour flight and representing a total of 8 flight hours per subject. These questionnaires and the resulting data were intended to provide insight into the "adaptation" to the hyperstereo vision in the HMD with expanded exposure.

Over the extent of the 8 flight hours, subject #1 reported the presence of ghost images for each night except the first; subject #2 reported this phenomenon only for the second and third nights (Question #2).

Subject #1 reported problems with depth perception on the first and last nights, but not for the two intermediate flights; subject #2 reported problems all four nights, particularly at heights above the ground below 200 feet (Question #3). Slope detection was not a problem for subject #1 but was difficult for subject #2 on all nights (Question #4).

Neither subject experienced any problems with unaided vision within the cockpit. Subject #1 reported an improved capability to view under (beneath) the TopOwl system (Question #8). Eyestrain was experienced by both subjects during virtually all flights.

When asked each night to provide opinions on advantages and disadvantages of the hyperstereo system, there were no consistent responses (Questions #10 and #11). Subject #1 listed weight and stability as advantages during the first flights but not for the later flights. Subject #2 listed the ability to "see through to the instruments (referring actually to the look under capability)" but only for the first night of flight. Subject #1 listed eye strain and the presence of double lights as disadvantages, but only for the first two nights. Subject #2 was more persistent with listing disadvantages: lack of tilt capability on the display, inability to use chin bubble, loss of (normal) depth perception cues, poor cross cockpit view, and cockpit obstructions.

Both subjects expressed the opinion that any approach to training students to use a hyperstereo system, as compared to ANVIS, would require a change in scanning techniques (to acquire a different set of visual cues) and a longer training time overall (Question #12). At the end of the first night of flight, neither subject was willing to estimate the amount of time they believed would be required to "become proficient with" the system. By the end of the 8-hour flight period, both subjects estimated 10 hours. This correlated very well to an identical 10-hour period estimation as a response to the question (#13b) of how many hours they believed they needed to become proficient in the flight tasks performed in this study.

Responses to Question #7 show the only major problem to be depth perception, with both subjects each night rating it as being "slightly worse" or "much worse" as compared to flying with ANVIS. Subject #1 rated several factors as "slightly better" as compared to ANVIS over the 8-hours of flight. These were low-light resolution, helmet fit, unaided visual field, and head-supported weight. This same subject consistently rated CM as "much better." Subject #2 did not identify any factors as better than with ANVIS. Subject #2 consistently rated bright light recovery, tube brightness, low-light resolution and gain, and halo size and intensity as, at best, "slightly worse" than with ANVIS, although the laboratory assessment did not measure any significant differences in resolution and gain at low-light levels and actually measured a slight improvement in halo size, as compared to a typical OMNI IV ANVIS. However, the subjects may have had less experience with OMNI V and VI ANVIS with smaller halos.

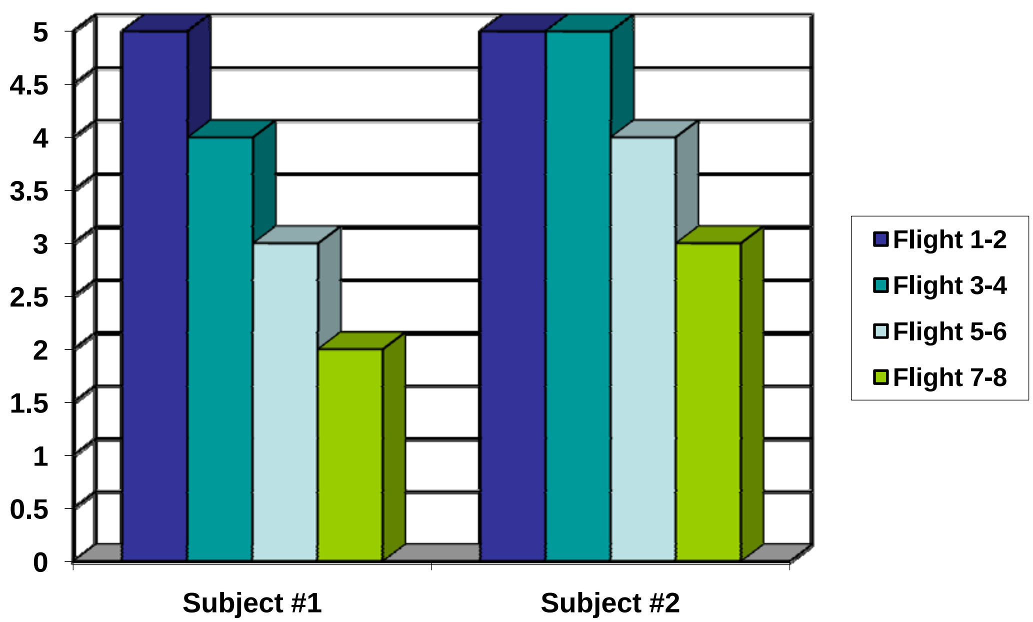
In Question #13b, subjects also were asked each night to indicate their agreement with the statement "Based on total flight experience with this system, I have become fully adapted to the hyperstereo visual effects." Each subject's series of responses are presented in figure 9, where it can be seen that the final rating of full adaptation is reported as 2 (Somewhat agree) for subject #1 and 3 (Neither agree nor disagree) for subject #2.

Both subjects reported the presence of multiple images over the successive night flights. Subject #1 reported multiple images of lights, especially colored lights; subject #2 reported his

multiple images being part of the aircraft structure (e.g., struts). Due the separation of the tubes, as the subject's head turned, a strut would be seen first by one tube and then by the second.

At the end of 8 hours of flight, both subjects agreed that they experienced conditions and flight time sufficient to evaluate the hyperstereo system (Question #15). Both subjects also agreed that, as a final assessment, they did not identify any performance enhancements from the use of the hyperstereo system. Other than mild eyestrain, experienced by subject #2, which was relieved when the system was removed, neither subject reported any residual visual problems following any of the flights.

See appendix G for individual subject responses to the post-flight questionnaire for the sequence of the four nightly flights totaling 8 flight hours per subject.



1- Strongly agree 2- Somewhat agree 3- Neither agree or disagree
4- Somewhat disagree 5- Strongly disagree

Figure 9. Level of adaptation over the 8-hour flight period, based on agreement with the statement: "Based on total flight experience with this system, I have become fully adapted to the hyperstereo visual effects"

In-flight interview questionnaire data

The in-flight interview questionnaire (appendix C) was administered during actual flight at the completion of each flight maneuver. While the specific questions for each maneuver varied slightly, the questions basically addressed the ability to judge height above the ground, presence of image distortion, detection and control of aircraft drift, and changes in head scanning method resulting from the use of the hyperstereo HMD. Subject responses to the interview questions were recorded on an audio channel and transcribed for analysis. Unsolicited subject comments and safety pilot feedback (e.g., true altitude readings following subject estimations) also were recorded.

A summary of individual subject responses to the in-flight questionnaire for each type of maneuver collapsed across all flights is provided in appendix H. The general trend in the responses, supported by representative subject quotes where appropriate, is attempted in table 8.

Major trends in the in-flight interview data include: underassessments of height above ground during hovers and approaches, which were moderately compensated for as flight time increased; changes in scanning patterns caused by inability to use chin-bubble and perform cross-cockpit scanning; failures to detect sloping ground; and minimal impact on performance during straight and level flight.

Table 8.
Summary of in-flight interview data.

Maneuver	**Question**	**Subjects #1-2 (8-hour flights)**	**Subjects #3-5 (1-hour flights)**
IGE Hover and land to ground (1)	a) Does the ground appear to be the same height as the radar altimeter?	Not for first 5-6 flights with ground being called at 6 ft; accurately estimated for last flights.	Two subjects reported depth illusions, estimating ground at 3-10 ft.
	b) During this maneuver, did you see any distortion in the image?	No	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	One subject reported having to change scan.	Generally, had to adjust scan.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	On subject reported inability to use chin bubble and perform cross-cockpit scanning.	Generally, had to adjust scan.
VMC takeoff (2, 7, 9 & 12)	a) Does the ground appear to be at the same height as the radar altimeter?	For initial flights, ground and trees appeared closer; for later flights, compensation occurred.	Initially, ground and trees appeared closer; for later flights, compensation occurred.
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	Generally, no.	Generally, no.
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No, for one subject; for second subject, mixed response.	Generally, yes.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Generally, not for this maneuver.	Generally, not for this maneuver.
	e) Did you notice any difficulty determining whether the climb out angle would clear the trees during any phase of the climb? (For 7 only)	Generally, no.	No.
Straight and level flight (3)	a) Does the ground appear to be at the same height as the radar altimeter?	Divided response.	Generally, yes.
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	No.	No.
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	Generally no, but complaints about inability to use chin-bubble.	Generally, yes.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Generally, no.	Generally, no.

Table 8 (continued).
Summary of in-flight interview data.

Maneuver	Question	Subjects #1-2 (8-hour flights)	Subjects #3-5 (1-hour flights)
VMC approach to a 10-ft hover (4)	a) Does the ground appear to be at the same height as the radar altimeter?	For all but last flights, ground appeared closer; "called 10 ft at 26 ft. "	Ground appeared much closer, "ground called at 10 ft."
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	No.	No, but one subject reported "windscreen and door appears to be smaller."
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	Mixed response.	Yes.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Mixed response.	Generally, no; but one subject reported having to scan both sides of the door.
Slope landing and takeoff to hover (5)	a) Does the ground appear to be at the same height as the radar altimeter?	No, the ground appeared closer; "it feels like my $%& is on the ground."	No, ground typically called at 4 ft.
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	Generally, no.	No.
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	Mixed response.	Generally, yes.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Generally, no; one subject reported having to close one eye to focus on strut; chin-bubble reported as useless.	Mixed response; one subject did not respond.
	e) Did you detect and estimate the slope the same as with goggles?	Very difficult to detect.	"Did not see slope at all"; "not able to see."
IGE hover with 360° turns (6)	a) Does the ground appear to be at the same height as the radar altimeter?	Generally, no. Aircraft appears closer.	No. Ground appears closer.
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	No.	Generally, yes; "can see an abnormal slope."
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	Mixed response.	Generally, yes; "loss of chin-bubble"
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Generally, no, but ghosting of structure reported.	Generally, no, but ghosting of structure reported.

Table 8 (continued).
Summary of in-flight interview data.

Maneuver	**Question**	**Subjects #1-2 (8-hour flights)**	**Subjects #3-5 (1-hour flights)**
VMC approach to ground (8)	a) Does the ground appear to be at the same height as the radar altimeter?	Generally, no; aircraft reported as closer to ground and approaching the ground at a faster rate.	Generally, no; called ground too high.
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	No.	No.
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	Mixed response.	Generally, yes; "chin-bubble useless."
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No.	No.
Roll on landing (10 &13)	a) Does the ground appear to be at the same height as the radar altimeter?	Generally, no; ground closer; improved for later flights.	Generally, no; ground called at 10-13 ft.
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	No.	No.
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	Generally, no; problem with cross-cockpit scanning.	Generally, yes; useful scan limited between 12 o'clock and 9 o'clock.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Generally, no.	No.
	e) Did the aircraft make contact before or after you thought it would?	For initial flights, ground contact was later than expected; improved for later flights.	Generally, contact later than expected.

Table 8 (continued).
Summary of in-flight interview data.

Maneuver	Question	Subjects #1-2 (8-hour flights)	Subjects #3-5 (1-hour flights)
Back taxi 50-ft deceleration (11)	a) Does the ground appear to be at the same height as the radar altimeter?	Generally, no; ground appears closer.	Yes for two subjects; one subject, no response.
	b) During this maneuver, did you see any distortion in the image? If yes, try to explain.	No.	No.
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	Generally, no.	Generally, yes; chin-bubble reported as useless.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Mixed response; "chin-bubble useless"; glare-shield interference.	Generally, no; one subject reported glare-shield blockage.
	e) Did the initiation of the decel maneuver seem normal for the distance?	Initially, decel rates not as expected; normal for later flights.	Generally, normal.

ANVIS/Hyperstereo HMD comparison questionnaire data

This questionnaire was distributed to all subjects following their last flight (appendix B). For subject #1-2, this was after 8 hours of flight; for subject #3-5, this was following their single 1-hour flight. Subjects were asked to compare their ability to perform maneuvers (appendix D) with the hyperstereo device to their ability with ANVIS. A 5-rank Likert scale of 1 to 5 was used, where 1 indicated "Much better than with ANVIS" and 5 indicated "Much worse than with ANVIS." The neutral rank of 3 indicated "Same as with ANVIS." Subjects also were asked to provide a similar rank across all maneuvers for both low- and high-light conditions.

A summary of these comparison data is provided in table 9. For the 1-hour subjects, the maneuvers involving roll-on and slope landings were judged as the most difficult to perform with the hyperstereo system than with ANVIS (rating of 5-Much worse than ANVIS.). For the 8-hour subjects, only the roll-on landing was judged as 4 (slightly worse than ANVIS). Across all maneuvers, two of the 1-hour subjects rated their ability as 4 (Slightly worse than ANVIS); the remaining 1-hour subject and both 8-hour subjects judged their ability to be "The same as ANVIS."

Discussion

Most HMD designs have sensor and/or optical components that are located in front of the eyes, forward of the head-neck CM. This situation is inherent to most versions of HMDs that are I^2-based. The CM shift increases fatigue and the dynamic loading present during crash

sequences. The presence of optical elements in front of the eyes also can increase the possibility of ocular and facial damage during crashes. (The use of break-away optics mitigates several of these injury factors [Shannon and Mason, 1997].)

Table 9.
ANVIS/Hyperstereo maneuver performance comparison.

Maneuver	**8-hr #1**	**8-hr #2**	**8-hr Median**	**1-hr #3**	**1-hr #4**	**1-hr #5**	**1-hr Median**
1- Much better then ANVIS 2- Slightly better than ANVIS 3- Same 4- Slightly worse than ANVIS 5- Much worse than ANVIS							
Hover and land to ground	4	3	**3.5**	4	5	4	**4**
VMC take off	3	3	**3**	4	3	3	**3**
Straight and level flight @100 feet AHO	3	4	**3.5**	4	3	3	**3**
VMC approach to 10-ft hover	3	3	**3**	4	4	4	**4**
Slope landing and takeoff to a hover	4	4	**4**	5	5	4	**5**
IGE hover @10 ft with 360° right pedal turn	4	3	**3.5**	4	4	4	**4**
VMC takeoff	3	3	**3**	4	3	3	**3**
VMC approach to ground	3	3	**3**	4	4	4	**4**
VMC takeoff pattern	3	3	**3**	4	3	3	**3**
Roll-on landing	3	3	**3**	5	5	3	**5**
Back taxi on runway 50 ft deceleration	3	4	**3.5**	4	3	3	**3**
VMC takeoff	3	3	**3**	4	3	3	**3**
Roll-on landing	3	3	**3**	5	5	3	**5**
Median across all maneuvers	3	3		4	4	3	
Under low light conditions for all Maneuvers*	3	4	**3.5**	4	5	3	**4**
Under high light conditions for all maneuvers	2	4	**3**	4	4	4	**4**
NVG hours	150	800		600	150	1100	

* Except for the first flight with subject #1, all flights were conducted under low light conditions or no moon. High light conditions were simulated by using the NIR searchlight that is required on Army aircraft for NVG training under low light conditions.

One engineering approach that addresses these concerns and allows the added capability of multi-sensor imagery is to move the I^2 tubes to the sides of the helmet. In implementing this design, the visual inputs to the two eyes are separated significantly beyond the typical IPD range

of 58-72 mm. A natural consequence of this engineering approach is a visual phenomenon known as hyperstereo vision, also referred to as hyperstereopsis. This phenomenon manifests itself primarily as exaggerated depth perception, causing objects in the near field of vision to appear closer than they actually are. In this investigation, the greatest difficulties reported by subjects, especially during initial flights, were experienced during low-to-ground flight tasks that required estimations of height-above-ground distances. Subjects consistently under-estimated their height above ground during hovers and roll-on landings, with subjects calling ground level at heights from 3-10 ft (1-3 m).

The classical vision literature on visual input rearrangements (e.g., use of prisms, mirrors, etc.) has been limited. What is available has reported that such relocations of inputs result initially in major disruptions in visual-motor coordination and visual perception, followed by a gradual adaptation. This adaptation is accompanied by performance recovery that approaches, but does not equal, premodification performance (Welch, 1986; Wildzunas, 1997). Most of these studies have involved such tasks as walking, ball tossing and other close-in, eye-hand coordination activities, none of which involved tasks and working distances more congruent to those associated with helicopter flight (CuQlock-Knopp et al., 2001; Judge and Bradford, 1988; Wildzunas, 1997).

Studies that have investigated hyperstereo in real aviation environments have been less extensive. With few exceptions, most military investigations have been trial flights or flight tests with an engineering emphasis (German Air Force Test Center, 1998; Kimberly and Mueck, 1991; Krass and Kolletzki, 2001). Consequently, while hyperstereo HMD designs have been available for several decades and several of these systems have been flight-tested, the high cost of flight tests has limited the study of long-term visual effects, especially the determination of an adaptation curve. This lack of data has prevented the attainment of a good understanding of whether the change in depth perception can be fully adapted to, or compensated for, with increasing exposure, which is important information needed to establish sufficient training requirements of these systems.

The ability of pilots to "adapt" to the depth perception differences induced by the hyperstereo viewing condition is of primary concern within the military aviation community, where perceptually-based judgment errors can have catastrophic consequences. However, the fielding of visual display systems that have required adaptation is not new to U.S. Army aviation. In the past decades, U.S. Army helicopter pilots have had to learn to fly with two HMD systems (the I^2-based NVGs [ANVIS] and the FLIR-based IHADSS) that present the external world in imagery that differs from that of normal human vision. Both of these systems have severely reduced FOVs and present scene content that is monochromatic, has lower resolution, and is populated with nonconforming visual cues (Rash et al., 1990; Verona and Rash, 1989).

An additional visual perception demand is present with the IHADSS. The pilot's perspective of the FLIR imagery is exocentric, in that the FLIR sensor is located approximately 10 feet forward and 3 feet below the pilot's design eye position (Rash, 2000). This exocentric

positioning of the imagery source can introduce problems of apparent motion, parallax, and incorrect distance estimation (Brickner, 1989).

These two systems are relevant to this discussion because they each present non-standard imagery that requires perceptual adaptation by new pilots. This adaptation apparently does transpire, at least to an acceptable degree, as both of these systems have been flown for more than two decades by hundreds, if not thousands, of Army pilots.

However, the non-standard differences in the I^2- and FLIR-based IHADSS imagery are relatively constant in form and type, facilitating adaptation. For example, with the exocentric location of the FLIR sensor used with the IHADSS HMD on the AH-64 helicopter, the displaced perspective is constant, allowing one mental model to always be applied. This is not the case with hyperstereo HMDs, where the depth perception effect is nonlinear and affected by motion rate.

In I^2 devices such as NVGs, the imagery differs from a normal visual scene by its monochromaticity (green on black) and in feature cue differences resulting from its spectral sensitivity, i.e., difference between the spectral sensitivity of the eye (visible spectrum of 380-780 nanometers) and of the filtered I^2- photocathode (partial visible spectrum into near infrared of 600-950 nanometers). The green on black characteristic of NVG images is constant. The effects of spectral response differences also are constant, but scene imagery can be greatly affected by ambient light level. But, more importantly, I^2 images are not spatially different. An object is perceived to be where it is, i.e., 10 ft is 10 ft.

Adaptation

The current investigation was too limited in flight time to fully address the issue of adaptation. Interestingly, the two 8-hour subject pilots moved from not adapted to being “somewhat adapted” and “neither agree nor disagree” to being fully adapted after 5 to 8 hours (figure 9). Whether this is a trend toward adaptation or simply a response to familiarity cannot be determined. It also should be noted again that this is their best judgment, as they were never allowed on the flight controls.

By definition, adaptation implies the development of the ability to adjust to new information and experiences. Through adaptation, we are able to adopt new behaviors that allow us to cope with change. This last statement is usually from a behavioral rather than a perceptual perspective. With hyperstereo, pilots can compensate by learning new behaviors for performing the maneuvers for which they have been trained. But, if presented with novel situations, they may not respond appropriately; this concern was raised by two of the subjects.

Pilots may not be “perceptually adapted” to hyperstereo but only behaviorally compensating. For example, when new glasses are prescribed for an individual, a moderate level of distortion may be present. But, after a period of use, the individual adapts and perceives the world as normal. This is an example of true perceptual adaptation. But, in studies where subjects were

asked to wear inverting prisms and perform everyday tasks, it was determined that subjects did not "see" the world as "up-right" instead, they learned to compensate for the inversion (Lindin et al., 1998). This is behavioral adaptation. This question of perceptual adaptation vs. behavioral compensation is perhaps the most important flight issue for hyperstereo HMDs.

Depth perception and stereopsis

Within a general scope, the functions of vision are to detect, recognize, and localize objects within the environment (McCormack, 1998). Binocular vision contributes to these goals via stereopsis, allowing judgments of distance and depth. Stereopsis also aids in the recognition of solid objects by providing three-dimensional cueing. Stereopsis is a binocular perception. It is the result of fusing two slightly different images of the same object, each formed from a slightly different perspective and falling on slightly different relative retinal locations when viewed by the two eyes.

According to McCormack (1998), the perception of the three-dimensional environment can be categorized into two processes: distance perception and depth perception. Distance perception is defined as the ability to judge absolute distances (in feet, meters, etc.) between an observer and an object or between two objects; this is sometimes referred to as absolute depth perception. Depth perception is defined as the ability to judge the relative distances between two objects (i.e., which is closer) and is referred to as relative depth perception. Many authors and researchers do not draw this distinction and use the phrase depth perception to encompass both absolute and relative depth judgments.

The cues for depth perception may be monocular and/or binocular. In rich visual environments, such as those encountered in the real world, the visual system uses both monocular and binocular cues to judge distances and to obtain perspective. These cues can have various impacts or weights on the visual interpretation process of depth perception. Landy et al. (1995) has shown that if two cues of high weight are in conflict, the relatively weaker cue will tend to be suppressed, as compared to an alternate scheme of an averaging of both cues. This scenario is highly likely in the military flight environment with night vision devices, requiring depth perception decisions to be based on the low contrast, noisy images present with these devices. However, regardless of the quality of the presented cues, there is little doubt that pilots use all possible available cues to reach the best estimates of distance and depth.

In the study presented herein, the effects of the degraded image quality on depth perception are further exacerbated by the presence of hyperstereo when flying with the test HMD. Subject experiences document this by reporting difficulty in estimating height above ground and the perception that near target objects appear closer than they actually are.

Subjects reported the greatest difficulties with hovering, takeoffs, and landings, especially roll-on landings and landings on sloping terrain. All of these maneuvers were at close proximity to the ground. The subjects reported that the effects of hyperstereo were less of a problem at during cruise flight at heights of approximately 100 feet (~30 m) AHO and became irrelevant at

altitudes of 200 ft (~60 m) or greater. This value must be taken as only one datum point as there will be individual variability and highly influenced by task and other factors. Dr. Chuck Antonio, in Croft (2006), based on experience flying several Navy HMDs with hyperstereo, indicated that the various effects diminished with altitude and loss of richness of environment. In the fixed-wing flight, he reported that these effects were mitigated as the distance from the ground or objects was increased, and by approximately 1,000 feet (305 m) were no longer perceptible. In a personal communication, Dr. Antonio indicated that the 1,000-foot value was extremely conservative (Antonio, 2006).

Stereopsis requires two laterally displaced inputs for the eyes or sensors. Ideal thresholds for stereopsis have been reported from 1.6 to 24 arcseconds, which is the difference in the eye convergence angles between two objects. For aviators, the passing value for stereopsis with the AFVT is 24 arcseconds (group D). In general, when the angle between the line-of-sight of an object and its perspective feature differences, or its binocular parallax angle, becomes smaller than about 1 minute of arc (60 arcseconds), the object will no longer be perceived in depth. At this point, monocular cues become increasingly important.

To investigate the reported disappearance of the exaggerated depth perception effects of hyperstereo at altitudes of 200 feet AHO, consider the diagram in figure 10, where simple geometry can be used to relate these functional distances to that predicted for hyperstereopsis using basic stereopsis vision theory. In the diagram, **D** represents distance to a target (A); **PD** is the baseline separation distance between two visual inputs (effective IPD); and **a** is the subtended angle. Since the binocular parallax angle for infinity is zero, the target object will be seen in stereoscopic depth when the angle **a** is equal to the stereoacuity threshold (Steinman et al., 2000).

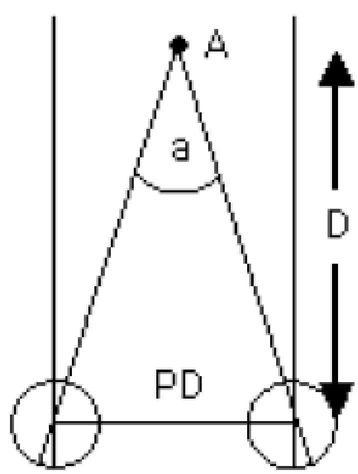


Figure 10. Maximum distance for stereopsis.

Based on simple geometry, the formula for the calculation is

$$\mathbf{\tan (a/2) = PD/2D,}$$

where **a** is expressed in radians. For the small angles of stereoacuity thresholds, $\mathbf{\tan (a/2) \approx a/2,}$ and the calculation can be simplified to

$$\mathbf{D = PD/ a}$$

For the TopOwl separation distance of 286 mm (0.286 meter) and using a stereoacuity threshold of 80 arcseconds (a conservative value used to reflect the effects of vibration, viewing through a dirty windscreen, etc.), the distance **D** is calculated to be

$$\mathbf{D} = 0.286 \text{ meters}/\ 3.879\text{E-4 radians} = 737 \text{ meters } (\sim 2400 \text{ feet}).$$

This distance is somewhat greater than the approximately 200+ feet at which subjects described the effects as moot. The discrepancy between the two distances is not surprising. First, the 200+ feet value should be interpreted as an altitude at which the hyperstereo effects were less noticeable and not necessarily totally absent. Second, in familiar environments, or at least in environments where there are familiar objects whose spatial attributes and relationships are known, monocular cues often override stereopsis. In addition, the theoretical distance values predicted by the formula are far removed from the actual flight scenario where the pilot is obtaining most of his/her stereoscopic cues from I^2 imagery that is low luminance, low contrast, and noisy.

Physiological effects

For this limited investigation, no significant changes in visual performance on stereo or phoria tests were found when measured pre- and post-flight using the AFVT. While the potential of long-term physiologic effects could not be answered in this limited study, it does bode well that no changes in visual performance were noted (table 5). In addition, in the nightly questionnaires, none of the subjects reported any visual follow-on effects after the flights.

Structural effects

The increased separation distance in the hyperstereo HMD did produce some additional comments and complaints. These complaints included the presence of multiple images of aircraft structural elements and outside lights. These complaints were constant and were not mitigated by increased exposure time. The multiple lights from each point source, however, were eliminated with the opaque FOV occluding visor (a Thales add-on feature), which was preferred over the see-through vision within the I^2 FOV.

Subjects reported that due to the placement of the airframe struts in relationship to the separation of the I^2 tubes, a single strut was perceived as two semitransparent struts. A related reported effect was that during head scanning notion, a strut would first be seen by one I^2 tube and then by the other tube, producing a fan effect. From previous studies and informal evaluations, these effects are highly dependent on aircraft type (i.e., frame design and strut separation and distance). During the study, the opportunity arose to evaluate this problem statically (i.e., while on the ground) in the front and rear seats of the U.S. Army's AH-64. From the front seat, the structural elements were judged as nonproblematic. However, in the back, the overhead longitudinal canopy rails were reported to be a major interference.

Another structural concern directly attributed to the UH-60 used in the study was the loss of the ability of the subjects to use the chin-bubble for takeoff and landing cues. This was a direct consequence of the physical design of the TopOwl, which due to a lack of tilt capability prevented the subject from easily looking directly down. As a result, subjects reported having to make changes in scanning patterns and choice of visual cues. In addition, because the chin-bubble is relatively close, it appears as doubled.

Very similar to the doubling problem with the chin-bubble issue is a complaint regarding cross-cockpit scanning. Several subjects commented on cross-cockpit scanning as being uncomfortable or disconcerting, e.g., the copilot, and objects within the cockpit were doubled and semitransparent.

Comparison of physical characteristics

In the post-flight questionnaire, all subjects compared the physical characteristics of the TopOwl to those of standard ANVIS and ANVIS imagery. These included engineering features (e.g., halo size and intensity, resolution, etc.), physical features (e.g., FOV, head-supported weight, CM, etc.), and image-related characteristics (e.g., distortion, depth perceptions, etc.). Using a Likert scale (1-Much better than ANVIS/5-Much worse than ANVIS), only depth perception had a median ranking of 5 (Much worse than ANVIS) across all subjects; this was not unexpected given other data (table 6). There were two additional characteristics – tube brightness and FOV – that presented a median rank of 4 (Slightly worse than ANVIS). Due to proprietary concerns, the tube brightness issue cannot be addressed. The FOV dissatisfaction is not clearly understood. The 40-degree circular FOV of the TopOwl matches that of ANVIS. It was considered that the IPD could have played a possible role in this characteristic. It has been suggested that the combination of exit pupil size and fixed IPD would restrict the obtainment of a nonvignetted FOV to users having an IPD range of 61 to 69 mm. One study subject (#1) had an IPD (61 mm) that fell at the lower endpoint of this range. This subject ranked the TopOwl FOV as 4 (Slightly worse than ANVIS). However, the other two subjects who also ranked the FOV as 4 had 63-mm IPDs, well within the considered acceptable range, if the eyes were equally positioned within the exit pupils. Any helmet rotation or asymmetry between eyes from the mid line could cause one eye to fall at the edge of the exit pupil with straight ahead vision, and outside the exit pupil with lateral eye rotation.

While no TopOwl characteristics were ranked as 1 (Much better than ANVIS), the characteristics of head-supported weight, CM, and unaided (look around) FOV were ranked as 2 (Slightly better than ANVIS). These ranks were supported by other data and validate several of the drivers for a hyperstereo HMD design. These possible advantages were mentioned during the subject orientation briefing.

TopOwl performance

Although the TopOwl HMD (I^2 component only) was an investigative tool in this study and not in itself an item of evaluation, its use did allow the gaining of certain knowledge about its

operation and performance. Most of this knowledge was a result of the thorough laboratory testing required to deem the HMD as flight worthy in terms of visual and optical performance. This assessment was performed by measuring a number of system parameters and by comparing the obtained values to those of an OMNI IV F4949 ANVIS. The OMNI IV ANVIS procurement initially began in 1996 for image intensifier tubes with improved resolution and gain compared to the previously procured ANVIS.

For most test parameters, the TopOwl HMD met or exceeded the performance of the OMNI IV F4949s. However, two areas of concern were noted: the HMD's fixed IPD setting and the visor that is used as an integral component of the visor projection system.

The exit pupil size and IPD range of the TopOwl was measured to be 12 mm vertical by 16 mm horizontal and a fixed IPD setting of 65 mm, respectively. This combination will very likely restrict the ability of users to obtain a nonvignetted FOV to those having an IPD range of 61 to 69 mm, estimated to be only approximately 77% of males and 54% of female U.S. Army personnel (Donelson and Gordon, 1991). The smaller percentage of females may sound counterintuitive but results from a smaller IPD 1^{st}-99^{th} percentile range (53-67 mm) and mean (61 mm) as compared to 75-72 mm and 64 mm, respectively. This also assumes that helmet alignment does not include any IPD asymmetry or helmet lateral rotation, where one eye could be closer to the edge of the exit pupil than the other eye.

Specific to the TopOwl HMD used in the study, but possibly to other visor projection HMD designs, the measured vertical prismatic deviation values for the "as-worn" position exceed the Department of Defense visor specification (MIL-V-43511C) allowable value of 0.18 diopter. This failure is a result of the pantoscoptic tilt of the visor. In virtually all respects, the visor itself is of high quality with no residual refractive error of distortion. However, the implementation of the tilt needed for the visor projection introduces the prismatic error, as measured in the "as worn position. This may not be an easy problem to solve. In doing so, in the visor mold, the back curve of the visor must remain exactly the same, with changes needed for the location of the center of the radius of the front curve to be displaced vertically in order to obtain vertical prism values within the helmet visor specifications. It is also very likely that the current TopOwl visor tilt with the resulting vertical upward displacement of the images may add to the exaggerated appearance of the ground.

NVG hours

Although the limited number of subjects precludes any statistical correlation analysis between subject pilot responses and total number of NVG flight hours, it may be of interest to look at this factor. Comparing the two 8-hour subjects, subject #1 had relatively low-time (150 NVG hours) as compared to subject #2 who had 800 NVG flight hours. Interestingly, across all maneuvers for which the hyperstereo HMD was asked to be compared to ANVIS (table 9), the least experienced subject rated the TopOwl as the same or slight better than ANVIS. The more experienced subject rated the TopOwl as slightly worse than ANVIS. However, for the 1-hour subjects, no such tendency was present, with all three subjects (150, 600 and 1100 hours) rating

their opinions on being able to perform all maneuvers with the TopOwl as being the same or slightly worse than with ANVIS. Any future investigations of hyperstereo HMD adaptation curves should include HMD experience as a factor.

Final comments

Several subjects expressed satisfaction with the approach of relocating the I^2 tubes from in front of the face and the resulting see-through or better see-around (the eyepiece) capability. The weight and CM characteristics of this HMD were recognized as advantages. Subjects also were, as aviators, very interested in the full capability of this design approach to provide both I^2 and FLIR imagery with symbology in a single package.

Study limitations

This flight study proved extremely valuable in providing insight into the visual perception effects that U.S. Army aviators would experience when flying an HMD design that induces the hyperstereo phenomenon. Based on the limited operational literature and discussions with other Department of Defense organizations, the observations and findings presented in the next section appear to be valid. Nonetheless, this investigation was conducted under the following constraints and limitations, and the interpretation and extrapolation of the findings should be measured accordingly:

- Limited number of subjects.
- Limited number of flight hours.
- Lack of full helmet fitting capability. Considerable care was taken to ensure a stable and comfortable fit. However, one 8-hour subject did experience some problems with hot spots that were reduced with additional adjustments.
- Limited pilot experience (pre-exposure) to hyperstereo vision. One subject mentioned that in-flight pre-exposure would have better prepared him for perceptual effects.
- Failure to be able to counterbalance high/low lunar illumination conditions.
- Lack of motor feedback due to subject pilots not actually on the controls.

The TopOwl HMD used in this study uses a custom fitting system. During the fitting process, other than a few complaints regarding ear cup pressure that was alleviated by repositioning, there was little evidence that helmet fit using the different sized liners and pads was an issue for the flights in this study. However, there is a sound recognition that proper helmet fit is critical to future studies.

Summary results, observations and findings

Within the caveats discussed above, there are the following results, observations and findings:

- Placing the I^2 tubes to the sides of the helmet can mitigate weight and CM offset effects experienced by users of OMNI IV-V NVG. Subjects liked the relocating of the I^2 tubes from in front of the face and the resulting see-around capability.

- The hyperstereo phenomenon is complex and difficult to completely assess in the visually-rich, yet demanding military operational flight environment such as flight with I^2 devices. The multitude of factors confounds the ability to isolate the hyperstereo component and there is the lack of a real-world vision engineering knowledge base for predicting visual performance in the presence of hyperstereo vision.

- However, even limited flight exposure has provided insight into the effects of HMD designs that produce this phenomenon.

- The effects of hyperstereopsis become moot at altitudes of 200 ft (~60 m) or greater. Most flight tasks above 100 ft (~30 m) probably can be successfully performed. Due in large part to the complex operational environment, this suggested upper limit to the hyperstereo effect differs significantly from that predicted, based theoretically on stereoacuity thresholds.

- For flight operations involving rotary-wing aircraft that call for a high percentage of low-level navigation flights, landings, and takeoffs in demanding environments, the visual impact of hyperstereo on depth perception and distance estimation introduces the possibility of a number of perceptual problems. The foremost perceptual problem is that the ground and near objects appears closer than they really are. While this error would seem to be in the direction of a greater margin of safety for aircraft contact with the ground, stopping the vertical descent too far above the ground for example during an autorotation could result in substantial aircraft damage.

- Subject pilot observations lend some support to claims that a moderate level of flight training (5-8 hours) will permit pilots to develop compensation techniques that allow adequate and safe performance on the majority of flight tasks performed in this study, but with the uneasiness and caution associated with a new learning experience. The one exception was landing on terrain slopes. Subject pilots did not feel confident, based on their observations, that slope landings could be mastered in 8-hours of hands-on flight exposure.

- Based on subject pilot observations, hands-on pilots using a hyperstereo HMD may have difficulties with hovering, takeoffs, and landings, especially roll-on landings and landings on sloping terrain.

- Subjects expressed concerns about being able to handle novel (not trained for) situations or extremely reduced cue environments while wearing the hyperstereo device.

- The impact of hyperstereopsis on performance ultimately rests on the degree and flexibility of behavioral compensations and perceptual adaptation to the distortions produced by hyperstereo vision. Study subjects estimate approximately 10 hours of flight experience would be needed to reach proficiency with the maneuvers performed.

- Complaints of multiple images of aircraft structural elements and outside lights were consistent and not mitigated by increased flight experience. However, the use of the modified opaque visor that blocked see-through vision within the I^2 FOV alleviated the occurrence of the multiple light sources. Subjects reported that due to the placement of the airframe struts in relationship to the separation of the I^2 tubes, a single strut was perceived as two semitransparent struts. A related reported effect was that during head scanning notion, a strut would first be seen by one I^2 tube and then by the other tube, producing a fan effect. From previous studies and informal evaluations, these effects are highly dependent on aircraft type, e.g., frame design and strut separation and distance.

- Cross-cockpit scanning was reported as uncomfortable since many objects and the copilot were visually doubled and semitransparent.

- The ability to use the chin-bubble in the UH-60 for takeoff and landing cues was prevented by the physical design of the TopOwl. This required a change from ANVIS in scanning patterns.

- When asked to compare their ability to perform the flight maneuvers flown in this study for ANVIS and the hyperstereo device, subjects #3-5 (based on 1-hour flights) collectively reported the greatest difficulty with roll-on and slope landings. When considered across all maneuvers, two of these subjects rated their ability to perform the maneuvers with the hyperstereo device as “Slightly worse than with ANVIS.” The third subject indicated no difference. Subjects #1-2 (based on 8 flight hours) collectively rated only slope landings as “Slightly worse than ANVIS.” Across all maneuvers (median value), both of these subjects rated the hyperstereo performance as being the “Same.”

- For this limited investigation, no systematic changes in visual performance on clinical stereo or phoria tests were found when measured pre- and post-flight using the AFVT.

- The prismatic deviation for the “as-worn” position of the TopOwl visor exceeds the Department of Defense visor specification (MIL-V-43511C) allowable value of 0.18 diopter. This failure is a result of the pantoscopic tilt of the visor. While the measured prismatic deviation was specific to the TopOwl, such deviation may apply to other visor projection HMD designs as well.

- Exit pupil size and IPD range specific to the TopOwl was measured to have a 12-mm vertical by 16-mm horizontal exit pupil and having a fixed IPD setting of 65 mm. This combination will result in a vignetted FOV for users with a narrow or wide IPD.

Recommendations

The foreseeable future for HMDs holds the promise of reduced weight, based on new materials and use of light weight displays, and the use of periscope relay optics and/or electronics to reduce or eliminate the need for hyperstereo designs. In the meantime, based on the knowledge and experience gained in this study, a number of recommendations for current and future hyperstereo HMD designs have been developed. These recommendations are loosely classified into two categories: possible changes in flight procedures, and potential research areas, the investigation of which will help to address further the usability and possible acceptance of hyperstereo HMDs in the rotary-wing cockpit. Inherent in the recommendations for future research is the need for subject pilots to be "on the controls," i.e., in actual control of the aircraft, which will provide the feedback necessary for an indisputable assessment of flight performance with a hyperstereo HMD design.

Operational mode recommendations

- Investigate potential of switching to monocular mode to eliminate hyperstereo for certain tasks.

- Investigate specialized training programs, probably with a minimum of 10 hours of light time using the hyperstereo HMD design that will be used.

Further research recommendations

- Investigate absolute and relative distance judgments associated with a hyperstereo HMD design.
- Investigate slope estimation in the presence of hyperstereo vision.
- Investigate the effects of velocity and acceleration on the hyperstereo phenomenon.
- Investigate the distance at which depth perception binocular cues are superseded by monocular cues when flying with hyperstereo devices.
- Investigate the threshold effective IPD that hyperstereo becomes a performance issue. This may be task and viewing distance dependent.
- Investigate performance adaptation curve for extended flight exposure. If and when adaptation is obtained, investigate how well the adaptation is retained for currency requirements.
- Investigate pilot acceptance and performance enhancement provided by the fully-integrated I^2, FLIR, and symbology capabilities of this design concept.
- Investigate NVG experience as a factor in establishing performance adaptation curves.
- Investigate the need for special training requirements for use of hyperstereo HMDs.
- Investigate operational consequences of transitioning between hyperstereo and unaided viewing.

The complex nature of hyperstereo vision is not well understood in the visually rich yet demanding aviation environment. The current understanding of this phenomenon is limited to

classical vision theory and could be greatly enhanced by in-flight research that can develop an operational understanding and engineering data base.

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Appendix A.
Post-flight hyperstereopsis questionnaire.

Evaluation Time: ____________

Subject ID Code ___________ Date___________ Beginning/ Ending_______/_______

TOPOWL first flight of the night __________ TOPOWL second flight ___________

Your Total number of NVG hours _________________ Age _____

Do you wear counterweights when flying NVGS? (Circle one) Yes No

Do you wear glasses/contacts? (Circle one) Yes No

Number of flights with test device __________

Cumulative flight hours with test device____________

Percent Moon Illum during flight ________ Cloud cover (%) _________ Visibility____________

Seat side (Circle one) Right Left

Answer the following questions:

1. Did you notice any difference in resolution between the right and left tubes? (Circle one)
   Yes No
   If **yes**, which tube was clearer? (Circle one) Right Left

2. Did you notice any ghost images of lights? (Circle one) Yes No

3. Did you notice any difference in depth perception? (Circle one) Yes No
   If **yes**, at what range and/or altitude was this difference most noticeable? _________

4. Did you notice any changes in slopes, particularly up or down slopes? (Circle one) Yes No
   If **yes**, please describe: ____

____

5. During the test flight, did you experience any of the following visual/physiological complaints: (Circle all that apply)

   Headache Double vision Eyestrain Other ________________________

Additional comments: ____

____

6. Did you notice any dimming of the image or loss of field of view as you looked towards the edges of the field of view? (Circle one) Yes No. If "Yes", could you adjust the helmet to correct for this? (Circle one) Yes No.

7. How would you compare the TOPOWL used on this flight with the standard NVG?
Rank each parameter using the following code, where the TOPOWL is:

1	**2**	**3**	**4**	**5**	**NA**
much better	slightly better	same	slightly worse	much worse	not applicable

Depth perception ________ Distortion ________

Bright light recovery ________ Tube brightness ________

High light Resolution ________ Low light Resolution ________

Scintillations ________ Low light gain _________

Halo size ________ Halo intensity _________

Head supported Weight ________ Center of Gravity _________

Unaided vision field of view _______ Image intensified field of view _________

Helmet fit ________ Helmet Stability _________

Other (______________________________) _________

*__Note for above answers- If you have any 1's or 5's, please comment on next page or back.__

8. Compared to the standard NVG, did you notice any difference with your UNAIDED vision (such as dark adaptation) with the TOPOWL when viewing either the instruments or outside the cockpit?

(Circle one) Yes No If **yes**, identify whether you were looking inside and/or outside and describe.

____

____

____

9. When you looked from inside the cockpit with your unaided vision to outside the cockpit through the TOPOWL image, did you ever notice <u>any</u> temporary blur or flicker of the image?

(Circle one) Yes No ; If **yes**, how long did it last in seconds or fractions of a second?

____

10. List any features of the TOPOWL that offer advantages over standard NVGs.

____

11. List any features of the TOPOWL that are disadvantages over standard NVGs.

____

12. Did you notice anything about the TOPOWL you would require a different approach to its use by either NVG students or NVG qualified pilots? (Circle one) Yes No If **yes**, specify please explain.

____

____

13a. **<u>If this was your first flight with this system</u>**, how would you respond to this statement: "By the end of the 50-minute flight I was able to fully adapt to the hyperstereo visual effects" (circle one)

1	**2**	**3**	**4**	**5**
strongly agree	somewhat agree	neither agree or disagree	somewhat disagree	strongly disagree

Using this 50-minute flight as a reference, how many flight hours do you feel you would need to become proficient in flight performance (i.e., reasonably adapted to the hyperstereo effects): _______ hours

13b. **<u>If you have multiple flights with this system</u>**, how many hours/minutes do you have flying this system? ____ hours, _____ minutes

How would you respond to this statement: "Based on my total flight experience with this system, I have become fully adapted to the hyperstereo visual effects" (circle one)

1	**2**	**3**	**4**	**5**
strongly agree	somewhat agree	neither agree or disagree	somewhat disagree	strongly disagree

Based on your cumulative flight time on this system to date, how many <u>total</u> flight hours do you feel you would need to become proficient in flight performance (i.e., reasonably adapted to the hyperstereo effects): _____hours

14. Did you detect the presence of multiple images (reflections)? (Circle one) Yes No If **yes**, please explain:

____

____.

15. Were the duration and conditions of this flight adequate to evaluate the TOPOWL? (Circle one)

Yes No If **no**, how much additional time and/or what type flight conditions would you recommend?____

16. Did you notice any interference in vision with TOPOWL due to aircraft structure? (Circle one) Yes No

If **Yes**, explain:____

____

17. Did you notice any enhancements due to the TOPOWL's hyperstereo? (Circle one) Yes No

If **Yes**, explain:____

____

18. Immediately after removing the Top Owl system, did you notice any alteration in your normal vision such as depth perception changes, double vision, or distortion of the real image?. If Yes, explain, to include how long it lasted:

____

____

19. Any additional comments?____

____

____

Appendix B.
ANVIS vs. Hyperstereo HMD comparison questionnaire.

ID____________ Date ____________

Total number hours of Top Owl time _______

Rank how well you think you could perform these maneuvers using the following scale:

1 = much better than with ANVIS
2 = slightly better than ANVIS
3 = same as with ANVIS
4 = slightly worse than ANVIS
5 = much worse than ANVIS

1. Hover & land to ground 3 times (Lowe)
   Rank _______

2. VMC take off -- (Lowe)
   Rank _______

3. Straight and level flight @100Ft AHO to RT 366 (low level corridor south)
   Rank _______

4. VMC approach to a 10 ft hover at RT 366
   Rank _______

5. Slope landing and takeoff to a hover--reposition to NW corner of RT 366 to high ground
   Rank _______

6. IGE Hover @ 10 ft with 360 right pedal turn
   Rank _______

7. VMC takeoff to Highfalls
   Rank _______

8. VMC approach to the ground (Highfalls)
   Rank _______

9. VMC takeoff traffic pattern (Highfalls)
   Rank _______

10. Roll on landing Highfalls (short runway)
    Rank _______

11. Back taxi on runway 50 ft Deceleration
    Rank ________

12. VMC takeoff to Cairns
    Rank ________

13. Roll on landing Cairns (long runway)
    Rank ________

14. See-through vision characteristic with Top Owl
    Rank ________

15. VMC takeoff --return to Lowe
    Rank ________

16. All of the above maneuvers under high light conditions
    Rank ________

17. All of the above maneuvers under low light conditions
    Rank ________

Comments: ____

Appendix C.
In-flight interview questionnaire.

1. **Hover and land to ground 3 times (Lowe Army Air Field)**
    a) Does the ground appear to be at the same height as the radar altimeter?
    b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    Comments: ___________________________
2. **VMC take off (Lowe Army Air Field)**
    a) Does the ground appear to be at the same height as the radar altimeter?
    b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    Comments: ___________________________
3. **Straight and level flight @ 100 ft AHO to RT 366 (Low level corridor South)**
    a. Does the ground appear to be at the same height as the radar altimeter?
    b. During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    Comments: ___________________________
4. **VMC approach to the Y 10 ft hover at RT 366**
    a. Does the ground appear to be at the same height as the radar altimeter?
    b. During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    Comments: ___________________________

5. **Slope landing and takeoff to a hover –reposition to NW corner of RT 366 to high ground**
    a. Does the ground appear to be at the same height as the radar altimeter?
    b. During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    e. Did you detect and estimate the slope the same as with goggles? (better or worse with TopOwl) .
    Comments: ___________________________
6. **IGE Hover @ 10 ft with 360 right pedal turn**
    a. Does the ground appear to be at the same height as the radar altimeter?
    b. During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    Comments: ___________________________
7. **VMC takeoff to Highfalls Army Air Field**
    a. Does the ground appear to be at the same height as the radar altimeter?
    b. During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    e. Did you notice any difficulty determining whether the climb out angle would clear the trees during any phase of the climb?
    Comments: ___________________________

8. **VMC approach to the ground (Highfalls Army Air Field)**
    - *a.* Does the ground appear to be at the same height as the radar altimeter?
    - *b.* During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    - *c.* To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    - *d.* Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?

      Comments: ______________________________
9. **VMC takeoff traffic pattern (Highfalls Army Air Field)**
    - *a.* Does the ground appear to be at the same height as the radar altimeter?
    - *b.* During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    - c. To determine drift and aircraft control during the last maneu*ver,* did you have to scan differently than with goggles?
    - *d.* Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?

      Comments: ______________________________
10. **Roll on Landing (Highfalls Army Air Field))**
    - *a.* Does the ground appear to be at the same height as the radar altimeter?
    - *b.* During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    - *c.* To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    - *d.* Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    - *e.* Did the aircraft make contact before or after you though it would?

      Comments: ______________________________
11. **Back Taxi on runway 50 ft deceleration**
    - *a.* Does the ground appear to be at the same height as the radar altimeter?
    - *b.* During the last maneuver, did you see any distortion in the image? If yes, try to explain.
    - c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
    - d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
    - *e.* Did the initiation of the decel maneuver seem normal for the distance? If no, did it seem to start too early or too late?

      Comments: ______________________________

12. VMC takeoff –return to Lowe Army Air Field

a. Does the ground appear to be at the same height as the radar altimeter?
b. During the last maneuver, did you see any distortion in the image? If yes, try to explain
c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
Comments: ________________________

13. Roll on landing Cairns runway 06

a. Does the ground appear to be at the same height as the radar altimeter?
b. During the last maneuver, did you see any distortion in the image? If yes, try to explain.
c. To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?
d. Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?
e. Did the aircraft make contact before or after you thought it would?
Comments: ________________________

Appendix D.
Flight maneuvers.

Maneuver 1.

10-Foot In-Ground-Effect (IGE) Hover and Land to Ground

The safety pilot hovered the aircraft over one point at an altitude of 10 feet (ft) above the ground level (AGL) on a constant heading. Each 10-ft hover was held for approximately 30 seconds; then, the aircraft landed vertically down. The maneuver was repeated two more times for a total of three hover maneuvers. The UH-60 Aircrew Training Manual Task, Conditions, and Standards were maintained by the flying safety pilot (U.S. Army, 2005).

Maneuver 2.

Visual Meteorological Conditions (VMC) Takeoff

The safety pilot performed the takeoff on a normal departure angle sufficient to clear obstacles in the flight path. Power was maintained as required to maintain a normal climb angle to clear obstacles and the aircraft was placed in trim above 50 ft AGL as enroute forward flight was coordinated.

Maneuver 3.

Enroute Straight Low-level Flight

The safety pilot flew the aircraft at approximately 100 ft above the highest obstacle (AHO). A constant airspeed with slight variations in attitude was maintained.

Maneuver 4.

VMC Approach to a 10-foot Hover (to a remote training site)

The approach to a 10-ft hover was initiated from the enroute altitude with airspeed terminating to a stabilized 10-ft AGL hover on a constant heading by the safety pilot. The approach entailed maintaining a constant approach angle clear of flight path obstacles with a progressive deceleration.

Maneuver 5.

Slope Landing and Takeoff to a Hover

The aircraft was repositioned from the hover point to a slope selected by the safety pilot. Slope angles varied from as little as 4 to 11 degrees laterally, with some variation in the pitch axis as well. The slope landings were performed by the safety pilot from a stable hover descending vertically with no lateral or forward-aft drift, then terminating on the ground with either the left or right wheel high.

Maneuver 6.

IGE Hove with 360° Turns

The safety pilot repositioned the aircraft over flat terrain maintaining a stabilized 10-ft AGL hover with minimum drift. Once cued, the safety pilot then began a slow left or right pedal turn while maintaining his position over the ground. A full 360° turn was completed.

Maneuver 7.

VMC Takeoff

Maneuver was as described previously.

Maneuver 8.

VMC Approach to the Ground (To a stage field with a short runway environment)

The approach maneuver was performed by the safety pilot as previously described. However, this approach was terminated to the ground versus to a hover. A constant approach angle clear of flight path obstacles was maintained by the safety pilot with a progressive deceleration and termination to the ground with minimal lateral drift

A VMC takeoff, as described previously, was executed.

Maneuver 9.

VMC Takeoff to Traffic Pattern Flight with Return

A normal takeoff was performed by the safety pilot, and a right traffic pattern was flown at 800 ft AGL and 100 knots indicated airspeed with a return approach for a rolling landing. The approach was initiated from the base pattern altitude while maintaining a constant approach angle planned to terminate within the first 1/3 of the landing surface area (runway).

Maneuver 10.

Roll-On Landing

The aircraft was progressively decelerated to touchdown by the safety pilot with some forward movement, and the aircraft brakes were applied to a full stop.

Maneuver 11.

Back Taxi Deceleration

The aircraft was back-taxied on the runway by the safety pilot and positioned on the arrival portion to set-up the deceleration maneuver. While at a stabilized 50-ft AGL hover, the aircraft was accelerated to an airspeed of approximately 20-35 knots then rapidly decelerated to a pre-determined point (the opposite end of the runway) and returned to a 50-ft hover.

Maneuver 12.

VMC Takeoff and Return

A VMC takeoff, as described previously, was executed. This maneuver encompassed enroute flight at 1000ft AGL and 100 knots to a different runway environment

Maneuver 13.

Enroute Flight with Termination to a Roll-On Landing to a Large Airfield Runway Environment

. A roll-on landing approach angle as previously described was initiated but with a planned termination to touchdown being at or near 40 knots ground speed. This faster roll-on landing was utilized to again determine the approach rate of closure and altitude as well as allowing the subject pilot to attempt to time the touchdown point.

The aircraft then was flown to the remote training site and maneuvers 4 through 10 were repeated by the safety pilot a second time before the aircraft was flown to the base field thus ending the flight.

Reference

U.S. Army. 2005. Aircrew Training Manual Utility Helicopter H-60 Series. TC 1-237.

Appendix E.
Laboratory assessment methods.

Physical measurements

Halo size

The halos were measured using two horizontally-mounted small light-emitting diode (LED) point light sources located 4.5 meters from the objective lenses of the image intensifier (I^2) systems. The horizontal separation of the LEDs was adjustable and measured using a millimeter (mm) scale. The LEDs and background intensities were adjusted to optimize the visibility of the halos for a specific I^2 system. A technician moved the LEDs apart until the observer, looking through the I^2 system, detected separation between the two halos (figure E-1). The technician then moved the LEDs toward each other until the observer reported the halos as just touching. This distance was recorded. The measurement was repeated several times, and the median for the readings reported. The only halo measurements obtained were only for the center of the field-of-view (FOV). Halo sizes are reported in milliradians (mr) and calculated based on an objective lens focal length of 27 mm.

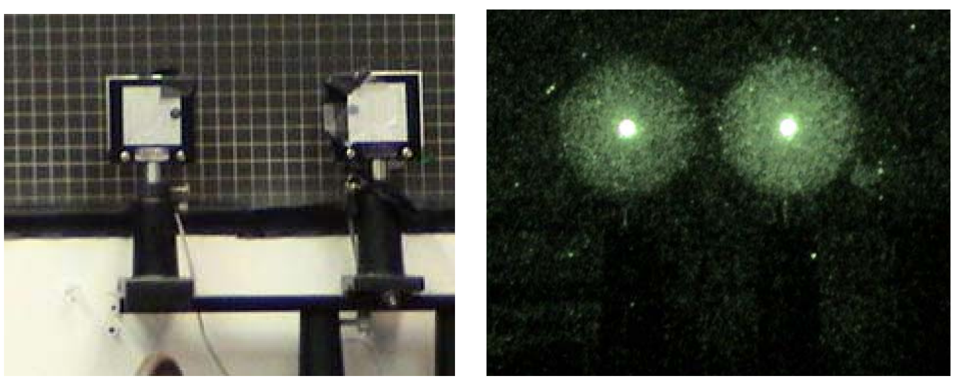


Figure E-1. Adjustable separation between green LEDs for measuring halo sizes.

Luminous gain (relative to OMNI IV&V)

To produce a uniform light source with a color temperature at approximately 2856°K, or Illuminant A, we used a HAAG-STREIT Goldman perimeter that used a rheostat to vary the output and color temperature of its incandescent light source. The background light source of the perimeter was adjusted until the color temperature readout from a Minolta Chroma Meter read approximately 2850°K. The perimeter background intensity could be changed without affecting the color temperature by adjusting a variable aperture. The background luminance was measured in foot-Lamberts (fL) with a Pritchard 180A photometer using a photopic filter, and a 1-degree aperture. The luminance outputs from the eyepieces of the I^2 devices were measured in fL with a model CS-100 Minolta Chroma Meter with a 1-degree aperture cone. A 250-mm close-up lens was added to the objective of the Chroma Meter. For the TopOwl, the Chroma Meter was focused at the exit pupil plane. For the ANVIS (F4949) comparisons, the Chroma Meter was focused at the plane of the eyepiece. The objective lenses of the I^2 devices were placed at the

center radius of the perimeter bowl. To measure and compare the relative gain of the systems, the background illuminance of the perimeter was increased until there was no increase in the luminance output from the eyepieces of the comparison ANVIS. This meant the I^2 tubes had activated the internal Automatic Brightness Control (ABC) circuit. Any further increase in background illuminance would not change the eyepiece output luminance. From the maximum eyepiece luminance out, the background illuminance of the perimeter was reduced with the variable aperture to ¾'s of the maximum value. This value assured there were no affects from the ABC, and true gain of the system could be determined when the measuring devices were well within their limits of sensitivity. Below ABC activation light levels, the luminance gain for image intensifiers is fairly linear. Without changing the background illuminance that produced the 3/4 value for the ANVIS, the TopOwl was positioned, and the output luminance was measured. To verify that the ABC level was not activated in the TopOwl, the background illuminance was increased to show an increase in the eyepiece output. Luminance gain (relative) was calculated by dividing the luminance output (fL) from the eyepieces by the effective luminance intensity (fL) of the background illuminance in the perimeter.

Maximum luminance for uniform field

The procedure for the maximum luminance output from the image intensifier devices was the same as the luminance gain, except the background illumination was increased until the ABC circuits were activated and no further increase in eyepiece luminance was shown as measured with the Chroma Meter.

C.I.E chromaticity coordinates (color of phosphor)

During the maximum luminance output, the CIE coordinates (x, y) were measured with the Minolta Chroma Meter. Additionally, a spectral scan from 380 to 780 nanometers was performed using a Photo Research Spectra Scan 704 spectroradiometer. For the TopOwl, the background illumination was adjusted until the ABC was activated. The spectroradiometer was focused at the exit pupil plane for the measurements.

Exit pupil size and shape

Unlike any of the currently-fielded aviator NVGs (e.g., ANVIS), the TopOwl is a pupil-forming system. To measure the on-axis exit pupil dimensions, a millimeter-ruler was moved in all three dimensions, oscillating the fore-aft movements around the exit pupil until the edges of the elliptical exit pupil was clearest. The clearest position of the exit pupil edges formed the smallest image of the exit pupil. The millimeter-ruler was positioned horizontally and vertically for these measurements.

As a second method (figures E-2 and E-3), a small charge-coupled device (CCD) camera with a 4-mm diameter objective lens was positioned at the exit pupil of the TopOwl and moved with a three-axis optical mount with 1-mm marked increments. The translucent (yellow) lens caps were retained on the objective lenses of the I^2 tubes to produce a nonimaged pattern, and the light

background illumination level was adjusted to activate the ABC levels in the I^2 tubes. The CCD camera was aligned along the center of the TopOwl FOV for one channel. As the CCD camera was moved in each axis independently, starting with the midpoint for the fore-aft adjustment, the monitor was viewed until the first sign of vignetting occurred at one edge of the FOV. The CCD camera then was moved in the opposite direction until a similar degree of vignetting occurred. The difference between these two positions was reported as the functional exit pupil dimensions for the vertical and horizontal components. Because of the limited testing time, the off-axis exit pupils were not measured. For such a measurement, the only difference in the procedure would be to position the alignment of the CCD camera towards the edges of the FOV at different angles and repeat the on-axis procedure, being careful to rotate the CCD camera at the equivalent of the center of eye rotation, or approximately 13 mm behind the front lens of the camera.

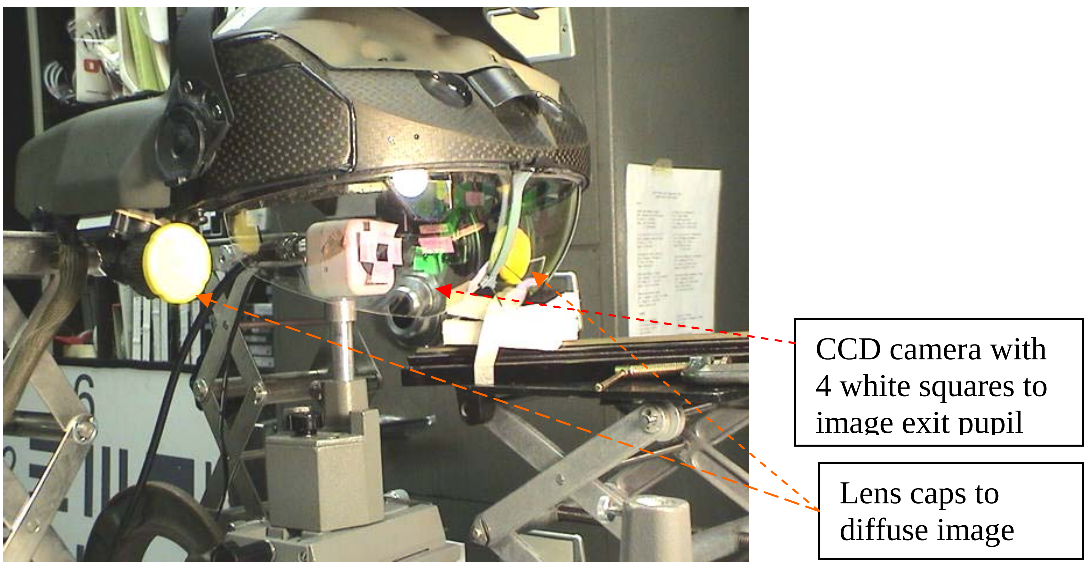


Figure E-2. CCD camera with three way adjustments (fore-aft, vertical, and horizontal)

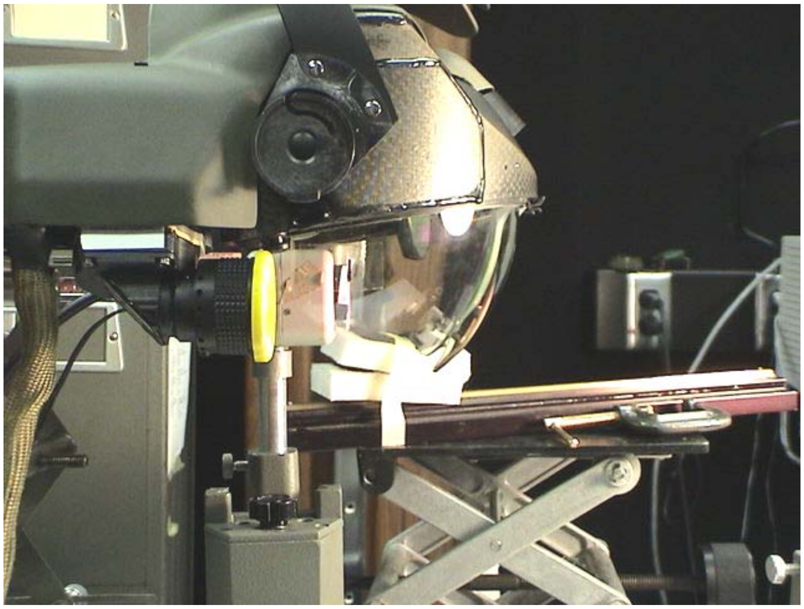


Figure E-3. The location of CCD camera and pantoscopic tilt of the visor.

Interpupillary Distance (IPD) range

By using the white diffuse reflective millimeter-ruler that was used to measure the size of the exit pupil, the right and left exit pupils were imaged on the ruler at the midpoint of the fore-aft position of the exit pupils. By measuring the distances between the nasal edges of the right and left exit pupils and the temporal (outer) edges, the middle IPD value (established as the mean), as well as the range of IPD values, could be determined. However, since a difference in the actual size of the exit pupil was found between the CCD camera and the millimeter-ruler methods, the functional range with individuals could be slightly different.

As a very quick and rough estimate of the range of IPD values that the TopOwl could accommodate, soldiers with a range of IPD values handheld the TopOwl display to optimize the exit pupil position and to determine if they had vignetting (edge shading or FOV loss) of the images. IPD values less than 61mm and more than 67-mm reported vignetting. To verify the vignetting, the soldiers would alternately look with one eye and then the other to center the image and detect any slight vignetting in each eye that corresponded to where the vignetting or FOV loss should occur for their IPD value. For example, narrow IPD individuals would report vignetting in the nasal right and left FOVs, and wider IPD viewers would report vignetting in the temporal FOV.

Physical eye relief (from visor)

The eye clearance measurement along the primary line of sight was an estimate at best. The right and left spherically curved visor components are tilted downward (pantoscopic tilt), and small alignment errors for head tilt will vary eye clearance measurement values by several

millimeters. The distance from the imaged exit pupil and the front of the visor was measured with a translating macroscope that has an electronic digital position gauge in 0.1-mm increments (figure E-4). The thickness of the visor was subtracted from the macroscope measurement to calculate the eye clearance value (i.e., the distance from the back of the visor along the primary line-of-sight to the exit pupil). The actual functional eye clearance value would be less than this value since the optimum placement of the exit pupil in the eye for minimum vignetting with eye rotation falls somewhere between the center of eye rotation and the entrance pupil of the eye. An estimate of the optimum location for the HMD exit pupil to the pupil of the eye is 2 to 3-mm behind the eye pupil or 5 to 6-mm behind the apex of the cornea (Shenker, 1987)

Eyepiece diopter setting

A ±1.00 diopter range diopterscope was used in this measurement. The marked increments are in 0.25-diopter steps, but the values can easily be interpolated to 0.06 diopter. An entrance pupil of 6 mm was added to minimize any spherical aberrations in the system. Calibration of the diopterscope to infinity was confirmed by first setting the diopter value at zero, and then focusing the diopterscope eyepiece for clearest cross hairs when viewing a distant object on the horizon. The diopter slide was moved from the zero point and then back into focus from both directions, verifying that the best focus point indicated was zero diopter. In the laboratory, a 1951 U.S. Air Force tri-bar resolution target was focused at approximately 4 meters while an

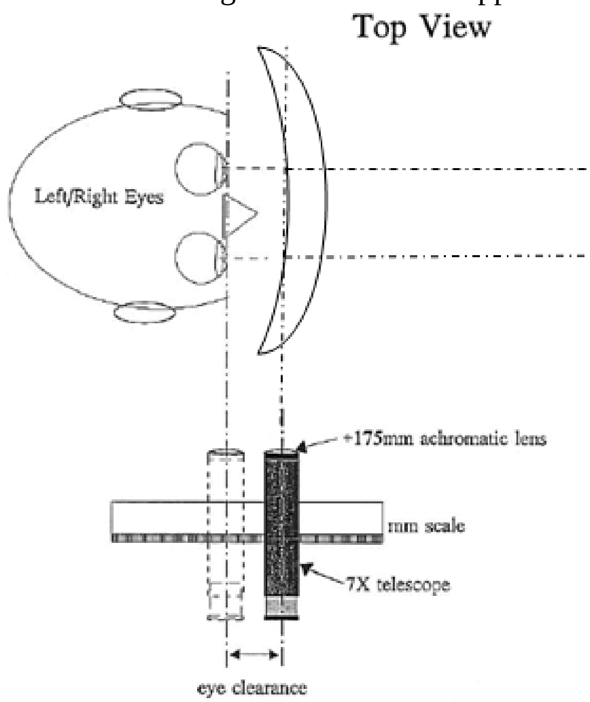


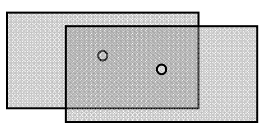
Figure E-4. Test set-up for measurement of physical eye relief.

experienced ANVIS observer viewed through the TopOwl. The TopOwl and diopterscope were mounted, and the diopterscope was placed so that its entrance pupil was at the exit pupil of the TopOwl; the intensified imaged then was focused. The background illumination was set just slightly above the ABC point for the I^2 tubes. The median of three values was recorded.

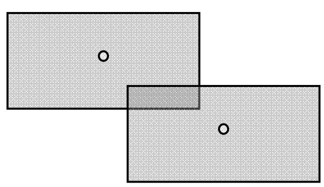
Collimation (I^2 alignment with see-through vision)

The presence of collimation means that the images viewed by the right and left eye, as seen through a binocular or biocular electro optical system, have no vertical or horizontal alignment imbalance or prismatic deviation imbalance. The right and left corresponding points of an image are connected by parallel rays. This does not necessarily mean that the virtual image and the real image are exactly aligned; they can be displaced vertically or horizontally to a slight extent. A device is considered collimated if the right and left images do not converge, diverge, or hyperverge (vertical imbalance) when imaging an object located at optical infinity.

The alignment of the images through night vision devices typically is verified and/or adjusted using a special test set, i.e., the TS3895A/UV or a Hoffman Model ANV-126 Night Vision Device Test Set. The binocular ANVIS has an adjustable IPD and is normally set to 75 mm to fit in the test set for the collimation determination. Two identical targets in the test set, located 75 mm apart and optically focused at infinity are used for the collimation test. The collimation attachment device uses a mirror and beam splitter arrangement to form a single angular path from two parallel image paths. If the two right and left centered circular dots fall in the overlapped rectangles, the device is considered collimated within specification. Figure E-5 shows the images in the test set when they are within and outside of the ANVIS tolerances for horizontal and vertical alignment.



Within tolerance

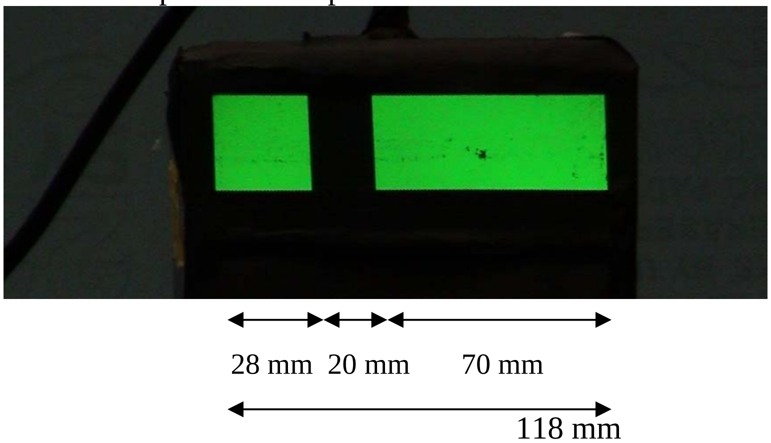


Outside of tolerance for both vertical and horizontal

Figure E-5. Images of targets in TS-3895A/UV within and outside of ANVIS collimation specifications.

The TopOwl system cannot be measured with these test sets. To verify collimation for the TopOwl, a different arrangement was required (figure E-6). An ANVIS-compatible fluorescent light was placed 5.6 meters from an observer using the TopOwl.

TopOwl tube separation of 300 mm.



Viewed at 5.6 meters, the 28-mm subtends 5 milliradians or 0.5 prism diopter.

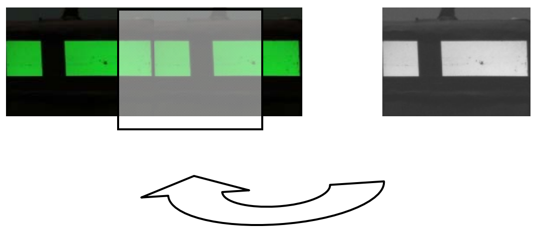


Figure E-6. Test set-up for collimation measurement for the TopOwl HMD.

The fluorescent light was viewed by an observer with 65-mm IPD. If the alignment (collimation) of the TopOwl was set for infinity, the I^2 images would butt next to each other with the see-through image fused. See figure E-7.

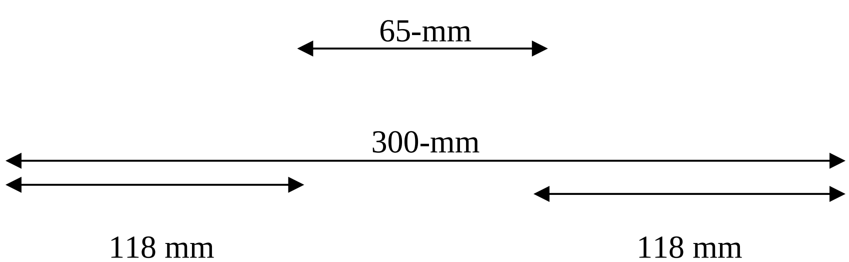


Figure E-7. Target dimensions required for the TopOwl collimation.

Visor transmission

The visor transmission was measured using a calibrated incandescent light source. Data was collected using a Photo Research Spectra Scan 704 scanning photometer scanning from 380 to 780 nanometers.

Visor refractive power

Measurements were taken with an American Optical prototype focimeter and a Humphrey Auto Lens Analyzer, Model 322 having increments for sphere and cylinder of 0.01 diopter. The visor was aligned in an "as worn" position.

Visor distortion

Visor distortion was evaluated with an Ann Arbor Distortion Tester using the specifications and test criteria from MIL-V-43511C (Department of Defense, 1990).

Visor prismatic deviation

Prismatic deviation values for the visor were measured with the Humphrey Auto Lens Analyzer. The visor was positioned in an estimated "as worn" orientation, based on the visor tilt angle measured with an inclinometer when positioned on a 50th percentile head form, as defined by USAARL Report No. 88-5 (USAARL, 1988).

Visor curvature and thickness

Visor curvature for the convex surface was measured with a Geneva Lens clock and the diopter value converted to millimeters of radius, assuming an index of refraction for the Geneva Lens clock of 1.52. The thickness was measured at a point within 30 mm of the edge of the visor using a lens thickness gauge with 0.1-mm increments.

Intensified image distortion

A digital camera was used to take pictures of a grid pattern, with and without the I^2 tubes activated. The without- TopOwl intensified image was taken under normal room illumination, and the with- TopOwl intensified image was taken under ANVIS-compatible light levels (figure E-8). The two images were compared visually for typical distortion patterns from barrel, pin cushion, trapezoidal, and irregular distortions.

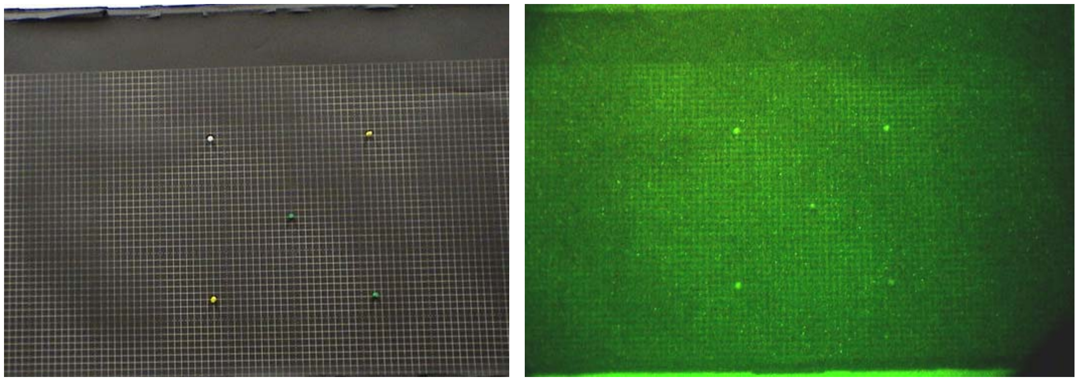


Figure E-8. Distortion pattern (left) and as viewed with TopOwl (right).

Physiological-based measurements

Visual acuity (VA) high- and low-light levels

The visual acuities were determined using a small standard issued NVG Test Set-TS4348/UV. This test set uses a near-infrared (NIR) LED, which is very stable over time. The primary purpose for checking the high and low resolution was to verify that the TopOwl provided performance at least equal to current ANVIS. This test set was used because the TopOwl will not fit in any of the standard authorized military test sets. The target in the test set is a modified 1951 Air Force tri-bar target. A single experienced NVG technical observer was used for these assessments. After the ANVIS and TopOwl were adjusted for optimum focus and resolution, the high-light acuity was taken using three observations. The low-light resolution was taken after 5 minutes of adaptation following the high-light assessments. Three readings were taken, and the median value was recorded. The subjectivity of this test was driven by the intent of the laboratory evaluation, i.e., only to ensure that the hyperstereo HMD provided the Army pilot subjects were being provided with the hyperstereo HMD being used in the flight study afforded equivalent or better performance than the standard ANVIS.

Response and recovery times to a flash of light

The light sources used for both the response and recovery time subjective observations were placed in a 6-inch diameter integrating sphere, outside the FOV of the I^2 viewing device. The light source for the initial response to an intense light was a NIR LED; the recovery source was a green LED. The F4949 and the TopOwl responses to the green LED were primarily from the NIR component in the spectral curve and to not the green visible component, which was filtered out with a minus-blue filter coating on the objective lenses of the I^2 tubes. The NIR LED had a peak spectral output at approximately 830 nanometers (nm) and was controlled by a function generator. The input signal was a square wave with a 1-second cycle (50% duty cycle). The voltage to the green LED used for the recovery component of the device was controlled with a fine-adjustment DC power supply.

The right objective lens of the Class B F4949 was positioned at the entrance to the integrating sphere (figure E-9). A Minolta photometer was focused to the plane of the eyepieces. The eyepiece output was adjusted to 0.20 fL (approximately starlight light level) for one tube. The response input from the NIR LED was selected and determined by placing a glass neutral density (ND) filter of 4.0 optical density (OD) in front of the objective lens and adjusting the NIR intensity until the luminance output from the eyepiece was approximately two-thirds of maximum or one-third below the Automatic Brightness Control activation with the neutral density in place. The ND filter was then removed for the tests. Measurements of NIR transmittance using the F4949 showed that the actual attenuation for these glass filters was approximately equivalent to an ND filter of 2.8 OD. Using the one tube from the F4949, these LED inputs were fixed and constant for the input to TopOwl. The LED inputs for the single tube from the F4949 were fixed, providing the same input to the TopOwl.

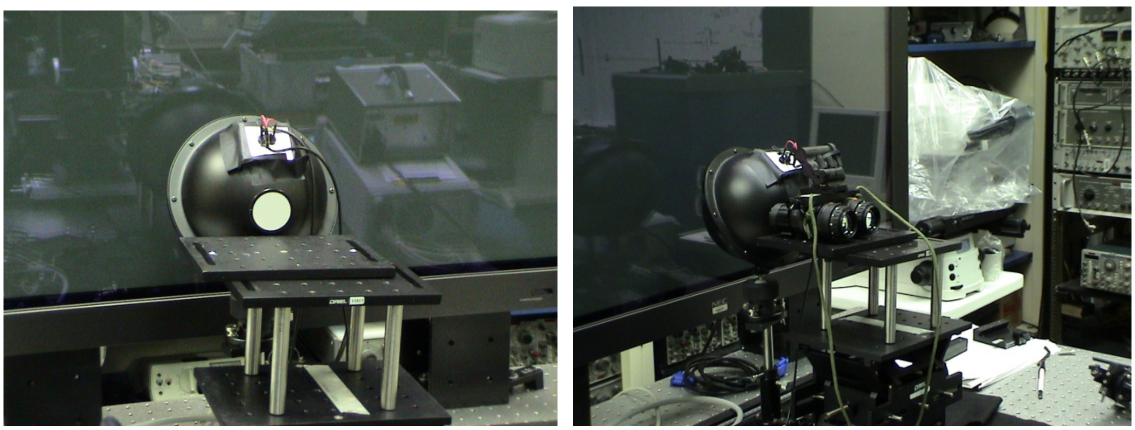


Figure E-9. Integrating sphere with and without OMNI IV ANVIS.

In previous work, measurements of the luminance output from the I^2 tubes vs. luminance input as a function of time have been performed using a Pritchard Photometer with output to a storage oscilloscope. However, for the quick assessment need for flight in this evaluation, subjective observation was used only for the purpose of determining the presence of gross time delays. Technical observers examined the glow from the eyepieces for the F4949 and TopOwl at a distance of two meters. The observations were made away from the eyepieces in order to reduce the short light and dark adaptations that would occur in response to the fast flash of light with a 40-degree FOV from the eyepieces. With the full FOV, the subject could not quickly adapt to the lower light level around starlight performance. The technical observers were requested to comment on any noticeable lags in the onset of the ABC function or recovery of the flashes.

References

Department of Defense. 1990. Visors, flyer's helmet, Military Specification, MIL-V-43511C, dated 16 July 90. Washington, DC.

Shenker, Martin. 1987. Optical design criteria for binocular helmet-mounted displays. SPIE Proceedings, Display System Optics, Volume 778, pp. 70-78.

U.S. Army Aeromedical Research laboratory (USAARL). 1988. Anthropometry and mass distributions for human analogues, Volume I, Male military aviators. Harry G. Armstrong Aerospace Medical Research Laboratory, Naval Aerospace Medical Research Laboratory, Naval Air Development Center, Naval Biodynamics Laboratory, U.S. Air Force School of Aerospace Medicine and U.S. Army Aeromedical Research Laboratory. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 88-5.

Appendix F.

Data for post-flight hyperstereopsis questionnaire for initial flights (Subjects #1-5).

Question	Subject #1	Subject #2	Subject #3	Subject #4	Subject #5
1. Noticeable difference in resolution between the right and left tubes	No	No	No	No	No
2. Notice any ghost images of lights	No	No	Yes	Yes	Yes
3. Noticeable difference in depth perception	Yes, close to ground at hover	Yes, at 100 foot range and below	Yes, at less than 10 feet AGL	Yes, low to ground and close to objects at VMC takeoff	Yes, noticeable nearest ground or obstacles
4. Notice any changes in slope, particularly up or down slopes	No	Yes, difficult to detect, determine up and down slopes	Yes, when landing, slope seem higher than actually is	Yes, view 9° slope as level ground when landing	Yes, slope was hard to detect especially when the slope is constant
5. Experienced the following visual/physiological complaints	Eyestrain; Helmet pain	Eyestrain; Neck strain from extreme scanning	Headache; Double vision	Eyestrain	Interference with armor panel
6. Notice any dimming of the image or loss of field of view when looking towards the edges of the field of view	No	Yes, can adjust helmet to correct this	No	Yes, only noticed when looking at bottom edge of image	No
7. Compare TopOwl use with standard NVG. Rank each parameter using: 1- Much better, 2- Slightly better, 3-Same, 4- Slightly worse, 5- Much worse					
-Depth perception	5, very hard to determine distance while hovering	5 – no comment provided	4	5, consistently difficult to determine, especially at low altitudes and on the ground	4
-Bright light recovery	3	3	3	N/A	5 – no comment provided
-High light Resolution	1, very clear picture	3	3	N/A	5, due to lower quality tubes used in this installation

Question	Subject #1	Subject #2	Subject #3	Subject #4	Subject #5
-Scintillations	N/A	3	3	2	4
-Halo size	3	5	3	2	5
-Head Supported weight	4	2	2	1, excellent balance ;like weight distribution better than ANVIS; ear cuff did not make a sound proof seal	2
-Unaided vision field of view	1, much easier to see instrument panel under tubes	2	3	5, worse, edge of clear visor created a structural illusion	1, unaided viewable area starts at edge of intensified area not blocked by monocular structure
-Helmet fit	4	3	5	5, did not fit snugly	4
-Distortion	N/A	3	5	3	3
-Tube brightness	2	4	3	4	4
-Low light Resolution	N/A	3	4	3	4
-Low light gain	N/A	3	3	N/A	3
-Halo intensity	3	4	3	3	4
- Center of Gravity	1, good helmet CG; fit good on head; did not shift	2	2	1	4
-Image intensified field of view	1, perceived FOV to be greater than 40°	4	4	4	3
-Helmet Stability	1, very stable and tight but caused pain and hot spots formed toward end of flight	3	3	2	4
8. Compared to standard NVG, notice of difference with UNAIDED vision with TOPOWL when viewing either the instruments or outside the cockpit	Yes, cockpit easier to see	No	No	No	No

Question	Subject #1	Subject #2	Subject #3	Subject #4	Subject #5
9. Notice any temporary blur or flicker of the image, when looking from inside the cockpit with unaided vision to outside the cockpit through TOPOWL image	No	No	No	No	No, with black visor in up position, bright lights are shown in three's (one aided, one unaided)
10. List any features of the TOPOWL that offer advantages than standard NVGs	FOV; stability	See through the instruments	Not enough experience	Weight and balance of the device on the helmet	Weigh less; better clearance from obstacles in the cockpit
11. list any features of the TOPOWL that offer advantages than standard NVGs	Helmet fit (tight); eye strain	FOV adjustments; tilt; poor ability to use chin bubble	Cross cockpit scanning is poor; ghost imaging	Depth perception; FOV alignment (had to look up to see FOV)	Restricted visibility outside cockpit due to structures; decreased visibility through windscreen
12. Notice anything about the TOPOWL, you would require a different approach to its use by either NVG students or NVG qualified pilots	Yes, ability to adapt to sight picture when low to ground	Yes, training time may be longer	Yes, requires time to develop terminal approach image	Yes, more training to accurately perceive depth perception	Yes, Distances estimation and depth perception cues would have to be rewritten; apparent distance from ground or obstacles make hovering and landing unsafe
13a. If first flight respond to statement: "By end of 50-min flight was able to fully adapt to the hyperstereo visual effects": 1-strongly agree, 2-somewhat agree, 3-neither, 4-somewhat disagree, 5-strongly disagree	5	5	5	4	5
13a. Using 50-min flight as a reference, how many total hours needed to become proficient in flight performance	Unknown	Unknown	15	5	6

Question	Subject #1	Subject #2	Subject #3	Subject #4	Subject #5
13b. Respond to statement: "Based on total flight experience with this system, I have become fully adapted to the hyperstereo visual effects": 1-strongly agree, 2-somewhat agree, 3-neither, 4-somewhat disagree, 5-strongly disagree	5	5			
13b. Based on cumulative flight time with this system, how many total hours needed to become proficient in flight performance	Unknown	No response			
14. Detect the presence of multiple images	Yes, reflections on colored lights	No	Yes, reflections present in brightly lit areas; opaque visor solved this	Yes, with dark visor up, lights were double images	Yes, not a problem with viewing dimly lit objects
15. Durations and conditions of this flight adequate to evaluate the TopOwl	Yes	No	Yes	Yes	No, 1 hr fitting plus 3 hr flight
16. Notice any interference in vision with TopOwl due to aircraft structure	No	Yes, poor cross-cockpit viewing and look down capability	Yes, left post and windscreen caused distortion in image and interference; center post interferes with cross-cockpit scan	Yes, all structural	Yes, scanning through chin bubble or opposite side aircraft is impossible
17. Notice any enhancements due to TopOwl's hyperstereo	Yes, enhanced FOV when scanning from left to right	No	No	No	No
18. Immediately after removing the TopOwl system, notice of alteration in your normal vision such as depth perception changes, double vision, or distortion of the real image.	No	Yes, eye strain relief	No	No	No
19. Additional comments	None	None	Image appears most to ANVIS TYPE III	None	None

Appendix G.

Time series data for post-flight hyperstereopsis questionnaire (Subjects #1-2).

Question	Subject #1				Subject #2			
1. Noticeable difference in resolution between the right and left tubes, which clearer	No	No	No	No	No	Yes, left	Yes, left	No
2. Notice any ghost images of lights	No	Yes	Yes	Yes	No	No	No	Yes
3. Noticeable difference in depth perception	Yes, close to ground at hover	No	No	Yes, hover	Yes, at 100 feet range and below	Yes; 100 feet	Yes, distance estimation is different, and below 25 feet	Yes, but much improved; 100-200 feet still tough
4. Notice any changes in slope, particularly up or down slopes	No	No	No	No	Yes, difficult to detect, determine up and down slopes	Yes, hard to determine slope angle more so than NVGs	Yes, hard to detect, poor discrimination ability	Yes, easier doing slopes in high light
5. Experienced the following visual/physiological complaints	Eyestrain; Helmet pain	Eyestrain; like reading low light for a long time	Helmet pain	No response	Eyestrain; Neck strain from extreme scanning	Eyestrain	Eyestrain minimal, ear pain due to poor ear cup fitting	No response
6. Notice any dimming of the image or loss of field of view when looking towards the edges of the field of view	No	Yes, can adjust helmet to correct this	Yes, can adjust helmet to correct this	Yes, can adjust helmet to correct this	Yes, can adjust helmet to correct this	No	No	No

Question	Subject #1				Subject #2			
7. Compare TopOwl use with standard NVG. Rank each parameter using: 1- Much better, 2- Slightly better, 3-Same, 4- Slightly worse, 5- Much worse								
-Depth perception	5, very hard to determine distance while hovering	4	4*	4*	5 – no comment provided	5	5	4
-Bright light recovery	3	3	3*	3*	3	4	4	4
-High light Resolution	1, very clear picture	3	3*	3*	3	4	3	4
-Scintillations	N/A	3	3*	3*	3	3	3	3
-Halo size	3	2	3*	3*	5	5	4	4
-Head Supported weight	4	1	2*	2*	2	2	3	3
-Unaided vision field of view	1, much easier to see instrument panel under tubes	2	1*	1*	2	2	3	3
-Helmet fit	4	3	2*	2*	3	3	4	3
-Distortion	N/A	3	3*	3*	3	3	4	4
-Tube brightness	2	3	3*	3*	4	4	4	4
-Low light Resolution	N/A	3	3*	3*	3	4	4	4
-Low light gain	N/A	2	2*	2*	3	4	4	4
-Halo intensity	3	3	3*	3*	4	4	4	4
-Center of Gravity	1, good helmet CG; fit good on head; did not shift	1	1*	1*	2	3	4	3

Question	Subject #1				Subject #2			
-Image-intensified field of view	1, perceived FOV to be greater than 40°	3	3*	3*	4	4	5	3
-Helmet Stability	1, very stable and tight but caused pain and hot spots formed toward end of flight	1	1*	1*	3	3	3	3
-Other		Honey combing in bright lights	*Subject wrote same so written in from 1st hr			FOV too high, needs to be adjustable		
8. Compared to standard NVG, notice of difference with UNAIDED vision with TOPOWL when viewing either the instruments or outside the cockpit	Yes, cockpit easier to see	Yes; inside; when viewing cockpit better FOV under the image	Same	No	No	No	No	No
9. Notice any temporary blur or flicker of the image, when looking from inside the cockpit with unaided vision to outside the cockpit through TOPOWL image	No	Yes; ½ sec	No	Same	No	Yes, 1-2 sec adjustment	No	No
10. List any features of the TOPOWL that offer advantages than standard NVGs	FOV; stability	Stability; weight	Same	Same	See through the instruments	Not many	None overall	Nothing significant- potentially FLIR, HUD

Question	Subject #1				Subject #2			
11. list any features of the TOPOWL that are disadvantages compared to standard NVGs	Helmet fit (tight); eye strain	Double vision (lights)	Same	Same	FOV adjustments; tilt; poor ability to use chin bubble	Poor performance and depth perception cues	FOV difficult to maintain poor focal range, poor cross-cockpit scan ability, much more difficult to estimate distance	Obstructions in cockpit, FOV adjustments
12. Notice anything about the TOPOWL, you would require a different approach to its use by either NVG students or NVG qualified pilots	Yes, ability to adapt to sight picture when low to ground	Yes; scanning, height perception	Same	Same	Yes, training time may be longer	Yes, different scan techniques, focal procedures	Yes, scan techniques, focus procedures	Yes, increased training time, external light use
13a. How many hours do you have flying this system?	No response	2 hr	6 hr	8 hr	2 hr	4 hr	6 hr	8 hr
13b. Respond to statement: “Based on total flight experience with this system, I have become fully adapted to the hyperstereo visual effects”: 1-strongly agree, 2-somewhat agree, 3-neither, 4-somewhat disagree, 5-strongly disagree	5	4	3	2	5	5	4	3
13c. Based on cumulative flight time with this system, how many total hours needed to become proficient in flight performance	Unknown	10	10	10	No response	6-8	6-10	10

Question	Subject #1				Subject #2			
14. Detect the presence of multiple images	Yes, reflections on colored lights	Yes, runway lights	No response	Yes, bright lights	No	Yes, structures	Yes, only when aircraft structure is obscuring FOV	Yes, with head movement
15. Durations and conditions of this flight adequate to evaluate the TopOwl	Yes	Yes	Yes	Yes	No	Yes, so far	Yes	Yes
16. Notice any interference in vision with TopOwl due to aircraft structure	No	No	Same as previous	No	Yes, poor cross-cockpit viewing and look down capability	Yes, poor cross-cockpit viewing, chin-bubble scan reduced	Yes, see above (cockpit posts)	Yes, tail rotor pedals in chin bubble glare shield; armor panel
17. Notice any enhancements due to TopOwl's hyperstereo	Yes, enhanced FOV when scanning from left to right	Yes, FOV while scanning	No	No	No	No	No	No
18. Immediately after removing the TopOwl system, notice of alteration in your normal vision such as depth perception changes, double vision, or distortion of the real image.	No	No	No	No	Yes, eye strain relief	Yes, mild eyestrain	Yes mild Eyestrain	No
19. Additional comments	None	None	None	None	None	None	None	None

Appendix H.
In-flight questionnaire data.

Maneuvers	**Questions**	**Subject #1 (8-hr flight)**	**Subject #2 (8-hr flight)**	**Subject #3 (1-hr flight)**	**Subject #4 (1-hr flight)**	**Subject #5 (1-hr flight)**
1. Hover & land to ground 3 times	a) Does the ground appear to be at the same height as the radar altimeter?	For first six flights: No, calls ground typically at 6 ft. For last flight: Yes	1st five flights: no, aircraft perceived as closer than actually was; last 3 flights height estimates and touchdown "dead-on."	"pretty close"	"When the aircraft is hovering it feels like it is in a bowl, looks like a significant slope where there is none."	No; consistently called ground heights of 3-10 ft.
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	Generally no; during flight #2, subject commented that electrical wires look bigger.	No	No	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Yes; for 7 flights. "Very hard left and right, requiring unusual neck maneuvers."	Yes; "distorted image through the chin bubble."	Yes; right cross-cockpit scan is useless.	No; however, cockpit scan useless.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No; "no difference, scan pretty much the same as NVGs."	Generally yes; " not able to use chin bubble, difficulty looking down that far"; "When looking across cockpit, quite a bit of distortion"	Yes; "have to scan out both sides of the door."	No	Yes; a little can see through objects.
	Additional comments	None	None	None	None	"Annoying that in order to see the image, I have to look up. Helmet is touchy to vertical movement."

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
2. VMC take off	a) Does the ground appear to be at the same height as the radar altimeter?	For first flight, "Looked like the aircraft barely cleared the trees. Would have pulled up with more power to climb faster." No problem after initial flight.	During initial flights, ground and trees appear closer; for the 6^{th} flight, subject over compensated calling 600 ft at an actual height of 500 ft; for last 2 flights subject perceived height accurately, but reported the task as challenging.	No; "Looks like the aircraft barely cleared the trees."	No; "Closer."	Yes
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No; "Clear image."	No	No	No	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Mixed response: No for earlier and later flights; yes for 5^{th} and 6^{th} flights.	Yes; "Have to scan both sides of door post."	Yes	Yes
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No; "Better."	Generally No, But during 3^{rd} flight difficulty looking around structure in the upper left quadrant. Double images reported.	No	No response	Yes; "When scanning in the other pilot sector, the structure definitely interferes with the field of view."

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
3. continued)	Additional comments	Structure blends in when scanning from left to right; eye strain reported during 2nd flight; "great vision underneath goggles (left support beam look invisible)." "Can see full panel by just looking down, do not have to tilt head back like with NVG"; for the 7th flight subject reports, beginning to have no problems clearing the aircraft.	When clearing trees they appear much closer than they actually are. During 5th flight, subject reported feeling more comfortable with this maneuver.	"Can see electrical wires fine."	"Takeoff looks appropriate, depth perception is off, but angle is fine."	"The takeoff looked normal."
3. Straight and level flight @ 100 ft AHO to RT 366 (low level corridor south)	a) Does the ground appear to be at the same height as the radar altimeter?	Yes: "Pretty close to what it should be."	Generally no, estimate heights higher than they actually are, e.g.; called 110ft at 100ft, called 250 ft at 160 ft.	Yes	No; "Aircraft appears lower."	Yes
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	No	No response	No response
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Mixed response. Subject continuously complains about inability to see through chin-bubble.	Yes	Yes	No

Maneuvers	**Questions**	**Subject #1 (8-hr flight)**	**Subject #2 (8-hr flight)**	**Subject #3 (1-hr flight)**	**Subject #4 (1-hr flight)**	**Subject #5 (1-hr flight)**
3. (continued)	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Generally, no; subject reports being able to “see through” the left strut.	No, however for 1st flight subject was bothered by ability to “see-through” structures.	No	Yes; “have to look up to achieve a full field of view.” (System most likely was sitting to high on subject head)	No
	Additional comments	Electrical wires look no different; for 5th flight subject reports, “Everything starting to look more normal.”	Struggling to maintain field of view. Need a pivot adjustment; “not seeing electrical wires as good as with NVG; “can see around structures”; for the 5th flight some double vision.	Acuity feels like a Type III or IV ANVIS.	Cannot see the electrical wires. When looking forward the subject has to tilt head, bring the glare-shield in to view.	Cannot see the electrical wires.

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
4. VMC approach to the Y 10 ft hover at RT 366	a) Does the ground appear to be at the same height as the radar altimeter?	During first 6 flights, no, with aircraft perceived much lower; for 1st flight subject reported thinking that he was going to hit the ground. E.g. 10 ft called at 21 ft; for 7th flight called 10 ft at 10 ft; for 8th flight, returned to calling 10 ft at 21 ft.	For first 6 flights, yes e.g. called 10 ft at 26 ft; called 2ft at 10 ft; for 3rd flight subject reported ground looking extremely close, as if about to hit, forcing him to look at the altimeter. For 6th flight subject reports at 10 ft hover looking like a 3-5ft hover when looking outside door, but looks correct as a 10ft hover when looking through front window. For 7th flight hover heights called correctly; for 8th flight subject was fairly accurate e.g. calling 40ft at 35ft, 12ft at 15ft.	No, a 10ft hover was perceived as 4ft.	No, called 5ft at 10 ft.	No, called ground at 13ft.
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	No	No	Yes; "Windscreen and door appears to be smaller."

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
4. (continued)	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Mixed response, with predominately yes.	Yes; "When scanning out toward right side of cockpit.	Yes	Yes; "Have to hold chin to chest to look out toward ground. Chin-bubble useless.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	Generally Yes; "have to turn head left a lot farther than with NVGs." (For 2nd flight)	Yes; having to scan both sides of the door.	No	No
	Additional comments	For 5th flight, subject stated that he was beginning to get use to the system.	"Very difficult to project slope. Similar to NVGs but worse with this system;" Subject reports great difficulty in using chin-bubble to acquire references and reports double images when looking in this area. For 7th flight subject reports crossing threshold where it is easier to accurately estimate heights.	No response	No problem when viewing straight ahead or 90 degrees out to the side, but double images reported when scanning out left door.	No response

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
5. Slope landing and takeoff to a hover – reposition to NW corner of RT 366 to high ground	a) Does the ground appear to be at the same height as the radar altimeter?	No; "felt as if the aircraft was below the level of the ground; 'It feels like my $&# is on the ground."	Generally no; "looks closer, called ground at 2ft, if actually flying would have grabbed the controls in fear." For 5ft flight, " looks like grass is up in the door"; for 8th flight, Yes, height perceived correctly	No (when looking out the window looks like I could reach out and touch the grass)	No;"Called 1ft at 13ft.	No; Called ground at 4ft.
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	Generally no; but some distortion reported on 3rd flight.	No	No	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No; for 5th flight subject reported that outside structures stand out more than on previous night (this report most likely due to difference in ambient lighting conditions).	Generally Yes (loss of chin bubble which is necessary to determine slope); cross cock-pit scan not good, have to farther out for reference point.	Yes	Yes; 'left window scan rendered useless."	No response
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	Generally no; for 5th flight subject reported having to close one eye in order to focus on air craft strut.	Generally no; for 5th flight yes, must use unusually slow scan to pick up terrain. For 8th flight yes, chin bubble useless.	Yes	No	No response

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
5. (continued)	e) Did you detect and estimate the slope the same as with goggles? (better or worse with TopOwl)	For first 5 flights No; "Could not tell the severity of slope because the grass looks like it is front of my face, if you look straight out you do not notice the slope it looks flat." For 6th-8th flight Yes, slope detectable.	Generally No; for the first 5 flights, slope at worse not detectable, at best, could be detected if considerable effort in using extra reference points. "Even though difficult with NVGs, this system exacerbates problem." For 6th and 8th flight subject reported feeling progress with estimating slope. However for 7th flight, subject estimated a 12-dgree slope to be 3-degrees.	Can detect the slope but worse.	No; "Did not see slope at all, it look leveled."	No; "not able to detect ground slope."
	Additional comments	None	"Not comfortable with performing this maneuver." Can more accurately tell the slope with NVGs. Subject reported that if he was flying this system with same slope perspective that as with NVGs, he would probably roll the aircraft.		Subject had difficulty seeing the cockpit power controllers.	Subject liked the fact that he could see the instruments without having to look around binocular tubes.

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
6. IGE Hover @ 10 ft with 360 right pedal turn	a) Does the ground appear to be at the same height as the radar altimeter?	Generally No; aircraft consistently appears lower to the ground, for 7th and 8th flight this difference decreases.	Generally No, Aircraft appears lower, for 2nd flight called 10ft at 24ft, for 7th flight a 10-ft hover "it felt like 3ft but I called it at 10."	No	No; "Objects appear closer and smaller."	Yes
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	Yes; "Image distortion when scanning out right side."	No	Yes; "can see an abnormal slope."
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Generally Yes; Loss of chin-bubble (necessary to determine slope). "When scanning out left door, the armor panel blocks the left ocular and because they are way out on the side, they pick up a lot more."	Yes	Yes	No
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	Generally No; for 7th flight subject reported becoming comfortable but, still indicated having problems with ghost structures, glare-shield, use of chin-bubble, and torque pedal. Subject believes that sling load operations while wearing this system would be a problem.	No	No	When scanning across cock-pit the subject reports ghost images and double images.
	Additional comments	None	"Chin-bubble is useless; no problem determining drift."	None	None	None

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
7. VMC takeoff	a) Does the ground appear to be at the same height as the radar altimeter?	No; “Ground appears a little higher.”	For 1st through 6th flights, No, the ground appears closer; for 7th and 8th flights, Yes.	Yes	No, feels like aircraft is only 10ft above trees when it is actually 15ft.	Yes
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	Yes, Chin-bubble distortion, double image.	No response	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Mixed response.	Yes	No response	Yes
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	Generally No; for 3rd flight Yes, “Cross-cockpit viewing is terrible, lots of double images, use of chin bubble is worthless.”	No	No response	No

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
7. (continued)	e) Did you notice any difficulty determining whether the climb out angle would clear the trees during any phase of the climb?	Generally No; For 2nd and 5th flight Yes, aircraft seems lower and looked it barely cleared the trees.	For 1st through 3rd flights No; “Trees look 10 feet away, actually 50 ft. For 4th through 8th flights, “Very comfortable and saw trees accurately.”	No; “Seem like a normal terrain takeoff.”	No response	No
	Additional comments	None	‘The glare-shield is cutting off the field of view.” Subject speculated that if performing an assault on a building for rapid deployment of troops that he would feel very uncomfortable with this system as compared to NVGs.	None	None	None
8. VMC approach to the ground	a) Does the ground appear to be at the same height as the radar altimeter?	No; “Looked like the aircraft was approaching the ground a lot faster”: called 13ft at 20ft.	Generally No, with aircraft appearing to be closer to ground. For 5th flight, ‘Called 80ft at 77ft, 18ft at 16ft and ground at ground.	No; “Called ground at 3ft, height is hard to judge, the aircraft feels like it is in a bowl.	Yes	No; Called ground at 18ft.
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	No	No	No

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
8. (continued)	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Yes; a lot of scan work out of the left side.	Yes	Yes	No, with the exception that chin-bubble is useless.
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	No	No	No	No
	Additional Comments	At 10ft the aircraft looks as if it was sitting on the ground.	Chin-bubble area is a problem. For 7th and 8th flight, “Cues are starting to look more normal, but determining slope still a problem.	None	None	None
9. VMC takeoff traffic pattern	a) Does the ground appear to be at the same height as the radar altimeter?	Generally No; aircraft seems to be a little higher.	For 1st and 2nd flight No, ground appears to be closer. For 3rd through 8th flight small discrepancies, e.g. called ground at 4ft, called 12ft at 7ft.	Yes for front window view; for side view, ground looks higher.	Yes	Yes
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	No	No	No

Maneuvers	**Questions**	**Subject #1 (8-hr flight)**	**Subject #2 (8-hr flight)**	**Subject #3 (1-hr flight)**	**Subject #4 (1-hr flight)**	**Subject #5 (1-hr flight)**
9. (continued)	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Generally Yes	No	Yes; glare shield blocking right ocular and strut blocking left ocular.	Yes
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	No	No	No	No
	Additional Comments	None	For 3rd flight subject states starting to feel very comfortable with this maneuver. For 5th flight, subject feel he could perform this maneuver with one problem.	None	Take off angle looks normal, but depth perception is really hard when looking across cockpit.	None

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
10. Roll on Landing	a) Does the ground appear to be at the same height as the radar altimeter?	For 1st through 6th flights, difficulty in height estimation; called ground at 15ft, "felt like the aircraft was falling through the ground." For 7th and 8th flight subject reports no difficulty.	For 1st through 5th flight mixed response. For 6th through 8th flight, Yes.	No, Called ground at 2ft aircraft feel like it is in a crater.	Yes	No, called ground at 13ft.
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	No	No	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	No	Yes	Yes	No
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	No	No	No	No
	e) Did the aircraft make contact before or after you though it would?	For 1st through 6th flight, "Way after." For 7th and 8th flight, about the same.	For 1st through 4th flight; after. For 5th through 8th; about the same.	No	Before	After

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
10. (continued)	Additional comments	For 3rd flight, subject reported eye strain. For 8th flight subject noticed double vision when queried.	For 2nd flight landing was closer than perceived, overcompensated in trying to reinterpret height: For 7th flight subject reports being comfortable with landing, big improvement from 1st flight.	None	None	Subject feels that it would be easier to adjust to the effects of hyperstereo if some time was spent in simulator first.
11. Back Taxi on runway 50 ft deceleration	a) Does the ground appear to be at the same height as the radar altimeter?	No; the ground always appears to be closer.	For 1st through 6th flight, ground appears closer; Called 10ft at 60ft, called 5ft at 20ft. For 7th and 8th flight, Yes.	Yes	Yes	No response.
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	No	No	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	For 1st and 2nd flight No, For 3rd through 8th Yes.	Yes, chin-bubble useless.	Yes, Chin-bubble useless.	No
	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No, can see clearly	For 1st through 5th flight Yes. Chin-bubble is useless. Too much glare-shield interference. For 6th through 8th No.	No	Yes, edge of glare-shield blocking right field of view.	No

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
11. (continued)	e) Did the initiation of the decel maneuver seem normal for the distance? If no, did it seem to start too early or too late?	For 1st and 2nd flight subject perceived decel as occurring to earlier. For 3rd flight too late; for 4th through 8th flight about right.	Mixed response in early flights, for 4th through 8th Yes.	Late	Yes	Yes
	Additional comments	None	For 1st flight, fighting with glare-shield; for 3rd flight uncomfortable with this maneuver; for 5th flight field of view issues.	None	None	Subject feels that NVG's are better because they set out front giving you a larger field of view.
12. VMC takeoff – return	a) Does the ground appear to be at the same height as the radar altimeter?	No	For 1st through 5th ground appears closer. Called 5th at 20 ft. For 6th through 8th, Yes.	No, but by making mental adjustment, called 25ft at 30ft.	Yes	Yes
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	Ghost images	Yes	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	For 1st Flight No, for 2nd through 8th flight Yes.	Yes	Yes	No

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
12. (continued))	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	No	No	No	No
	Additional Comments	None	Use to having chin-bubble with precision hovering, cannot be used with this system. Cockpit viewing is chopped up.	None	Used opaque half way down to block glare-shield.	None
13. Roll on landing	a) Does the ground appear to be at the same height as the radar altimeter?	Generally No, the tail looks like it is touching the ground when the actual height is much higher.	For 1st through 4th No, called ground at 5ft and the called ground at 2ft. For 5th through 8th flight; consistently called ground at ground.	No, called ground at 5ft.	No, called ground at 3ft.	Yes
	b) During the last maneuver, did you see any distortion in the image? If yes, try to explain.	No	No	Ghost images.	No	No
	c) To determine drift and aircraft control during the last maneuver, did you have to scan differently than with goggles?	No	Generally Yes; cross-cockpit scan worthless.	Yes	Yes, useful scan limited between 12 o'clock and 9 o'clock.	No

Maneuvers	Questions	Subject #1 (8-hr flight)	Subject #2 (8-hr flight)	Subject #3 (1-hr flight)	Subject #4 (1-hr flight)	Subject #5 (1-hr flight)
13. (continued)	d) Did you notice any interference in your scan from aircraft structures during the last maneuver? If yes, could you modify your scan and obtain the same information?	No	For 1st through 5th flights Yes: For 6th through 8th flights No.	No	No	No
	e) Did the aircraft make contact before or after you thought it would?	For 1st through 3rd flight after; for 4th flight before; for 5th through 7th flight pretty much right on; for 8th flight after.	For 1st through 4th flights After; for 5th through 8th flight same time.	After	After	At the same time.
	Additional comments	When subject asked to judge height at 1000 feet he estimated 500 ft. Saw multiple images with the runway lights.	Glare shield, a big problem.	None	None	None

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